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Ergonomics of human-system interaction —

Part 312:
Readability of electrophoretic displays

Ergonomie de l'interaction homme-système —

Partie 312: Lisibilité des écrans électrophorétiques

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Foreword

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This document was prepared by Technical Committee ISO/TC 159, *Ergonomics*, Subcommittee SC 4, *Ergonomics of human-system interaction*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

A list of all parts in the ISO 9241-300 series can be found on the ISO website.

Introduction

Electrophoretic technology has led to the development of reflective e-paper displays (EPD) that have fundamentally different optical characteristics compared to emissive display devices, such as backlit liquid crystal displays (LCD) or organic light emitting diode displays (OLED). EPD are used in reading devices, also known as e-readers. See Annex A for more information on the standardization of electronic displays.

The ISO 9241-300 series provides requirements from the viewpoint of human beings' visual properties and are organized by subjects.

Electrophoretic EPD were selected for the experiments reported in this document because of their widespread use as electronic reading devices.

Ergonomics of human-system interaction —

Part 312:
Readability of electrophoretic displays

1 Scope

This document provides an overview of recent research on readability of electrophoretic displays. It also provides information for evaluating readability of electrophoretic displays and defining the context of their use.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
visual analogue scale
psychometric response measurement scale

3.2
legibility
ability for unambiguous identification of single characters or symbols that may be presented in a non-contextual format

[SOURCE: ISO 9241-302: 2008, 3.3.35]

3.3
readability
characteristics of a text presentation on a display that affect performance when groups of characters are to be easily discriminated, recognized and interpreted

[SOURCE: ISO 9241-302: 2008, 3.3.38]

3.4
electronic paper display
EPD
electronic display that shows information by diffuse reflection and holds the image with low power consumption

3.5
electrophoretic display
electronic paper display (3.4) which forms an image by rearranging charged pigment particles using an applied electric field

4 Literature review on readability and legibility for electronic paper displays

4.1 General

A human action of reading is basically analysed by two subjective attributes, that is, readability[1] and legibility[2].

4.2 Readability for electronic paper displays

In 2006, Alex Henzen, et al. suggested that the EPD[3] would provide a reader with "immersive reading"[4]. Another paper reported that the viewing distance for EPD was similar to that of VDTs at around 500 mm, but greater than normal paper, at about 360 mm[5].

In 2007, An-Hsiang Wang reported on the visual performance for bending/curvature EPD.[6] This study indicated a future fashion of EPD, but require further exploration with progress of radiometric measurements. Wang also reported on the reading comprehension of subjects under several ambient illuminance conditions for electronic displays[7].

In 2009, there was a report on the difference of usability between EPDs and conventional books[8], but it was difficult to generalize, considering the results were based on a group of 20 university students. I-Hsuan Shen, et al. studied the visual performance and visual fatigue from EPD and found that a greater illumination than 700 lx was necessary.[9] Wang studied the effects of ambient illuminance on EPD and concluded the following:

1) under lower illuminance of 50 lx, the conventional LCD with a transmissive mode was the only choice;

2) under higher illuminance of 500 lx, the EPD can perform as well as the conventional LCD[10].

In 2010, Wang studied the visual performance of those subjects who were advancing in age[11].

In 2011, Der-Song Lee, et al. investigated the effects of light source, ambient illuminance, character size, and interline spacing on visual performance and visual fatigue for reader of electronic displays.[12] H.C. Wu studied the preferable viewing distance and character size for EPD and suggested that age factors can be considered for EPD design and VDT guidelines[13].

In 2012, Wang examined the effects of text/background colour combinations under three levels of ambient illuminance on the discriminating performance of young and elderly subjects.[14] This e-paper became a guide for the designers of colour EPD. Monika Pölönen, et al. evaluated eyestrain, visually induced motion sickness, changes in visual functioning, user experience, and the essential optical parameters of reading equipment for near-to-eye displays such as small size displays (of mobile phones) and paper.[15] The results indicated that reading from a hard copy was the most comfortable experience.

Wang, et al. investigated the effects of bending curvature EPD[16], but the sample size was too small to estimate effectively the effects.

Eva Siegenthaler, et al. concluded that the image quality seemed crucial for reading against the expectation of differential effects for reading between EPD and LCD.[17] Siegenthaler, et al. also analysed the reading behaviour between EPD and tablet LCD with an eye-tracking measurement.[18] The participants showed no difference in fixation duration, but there were significant differences in reading speed in the proportion of regressive saccades under special artificial light conditions. C. Connell, et al. studied the reading comprehension of subjects using EPD and tablet LCD.[19] The results indicated that the subjects read printed material faster than EPD and tablet.

In 2013, Po-Chun Chang, et al. investigated the effects of ambient illuminance and light source on the reading performance of 100 participants as well as visual fatigue as they read three types of reading tasks on an EPD and paper text.[20] This paper showed that the reading speed depended on ambient illuminance. Simone Benedetto, et al. studied the effects of display technology on visual fatigue over an average period of 10 days. Their evaluation was to measure the blinks per second of each subject and the visual fatigue scale. The results suggested that reading on tablet LCD triggered higher visual fatigue compared to both EPD and paper[21].

In 2014, M. Miyao started to investigate readability of EPD compared to LCD and printed paper under various ambient illuminance levels[22] to [30]. The advantage of the experiment was to employ more than 100 participants and to analyse the results by elaborate statistical processing.

In 2015, S. Matsunami investigated the readability of EPD for aging under various illuminance levels[31].

4.3 Legibility

By definition, legibility is closely related to typeface design. The typeface design went through changes from type-casting of lead block to outline font of font data on a computer. The outline font is scalable and enables desktop publishing (DTP) with increasing display resolution. In the past, bitmap font existed on a low-resolution display but was not scalable. With the beginning of DTP, the idea of page layout on a computer emerged in the 1980s, although page layout was originally omnipresent in the printing industry and publishing world from the age of movable type. Page layout has clearly become conscious of readability, as proved by the large sales of books in the field of printing and publishing business.

In the field of visual information processing, it is commonly believed that there is a unified concept: shape perception is explained by spatial frequency. Every shape responding to visual stimulus can be described as a composite function with a various sinusoidal wave by Fourier analysis of its contrast function. Elements of the contrast function are contrast sensitivities to various sinusoidal waves[32].

There has been a great deal of research in this fields[33].

5 Overview

This document explains the following 7 evaluations and results related to readability of EPD:

1) readability evaluation for EPD under 14 levels of illumination conditions (Clause 6);

2) proposing a baseline setup for readability using VAS evaluation (Clause 7);

3) verification of the minimum illuminance for readability of an EPD (Clause 8);

4) contribution of character sizes to the readability of mobile devices (Clause 9);

5) difference in readability of the contrast ratio of mobile devices (clause 10);

6) the effects of long-term reading on visual functions and subjective symptoms (Clause 11);

7) evaluation of readability for tablet devices by the severity of cataract cloudiness (Clause 12).

Equipment used in these reports:

— 6-inch ILU-EPD: Kindle®[1)] Paperwhite (2012 model);

— 9,7-inch EPD: Kindle®[1)] DX;

— 9,7-inch backlit LCD: iPad3®[1)] (2012 launched) model: A1416.

Kindle®[1)] is used due to its widespread use as an electronic reading device.

1) Kindle and iPad are trademarks of products supplied by Amazon and Apple, respectively. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of these products.

6 Readability evaluation for EPD under 14 levels of illumination conditions

6.1 General

The readability of EPD with and without integrated lighting unit (ILU) was compared to liquid crystal display (LCD) with backlight and printed paper to evaluate the contributions of built-in front- or backlights on the readability under different ambient illuminance levels from 10 lx to 8 000 lx. The comparison was carried out under a wide range of illuminance levels. Readability was evaluated using short English words[22].

6.2 Evaluation condition

6.2.1 Equipment

a) 6-inch ILU-EPD

b) 9,7-inch EPD

c) 9,7-inch backlit LCD

d) conventional paper as a reference (whiteness 69 % copy paper)

6.2.2 Participants

a) Number: 110

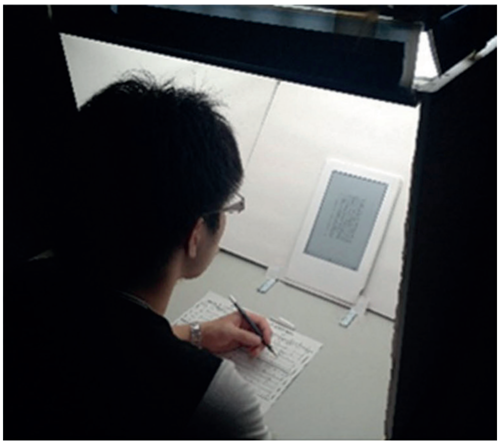
b) Gender: male (56), female (54)

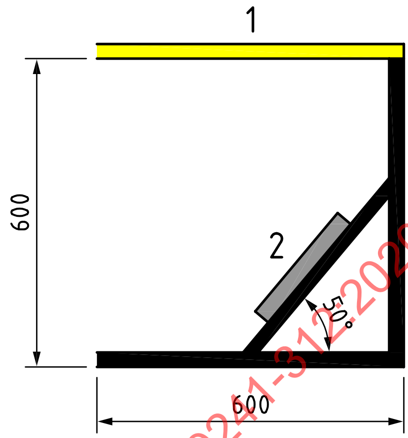
c) Age: from 19 to 86 [mean: 45,7, standard deviation (SD): 17,8]

6.2.3 Illumination condition

Ideally, it would be best to measure the readability under natural surroundings but those are not stable and they vary through time. Artificial stable lighting circumstances were created for 110 participants to make several statistical comparisons. For immersive reading, a small compartment was developed to produce stable illumination conditions. The compartment was set on a desk in a dark room for optical measuring. Its structure is shown schematically in Figure 1. Its light source was D65 by certified fluorescent lights (6 500 K). The illumination level was adjusted incrementally based on sophisticated electronic circuits. Relations between set values and actual measured values of illuminance are shown in Table 1.

Dimensions in millimetres





Key

1 lighting system

2 EPD

Figure 1 — Compartment structure

Table 1 — Illuminance value table

Set value	Measured value lx
10	13,47
20	22,73
50	51,60
100	101,4
150	151,4
200	176,3
300	261,7
500	516,7
750	787,7
1 000	1 042
1 500	1 591
2 000	1 983
5 000	4 670
8 500	8 017

6.2.4 Task (Evaluation methods)

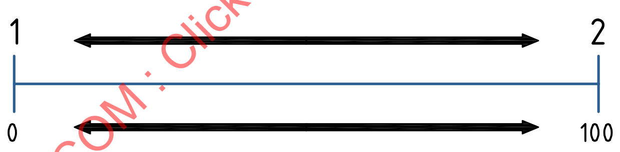
1) The participants read aloud short English words in 9-point (3,18 mm in height) Times New Roman font, black-on-white background, shown on a display for 15 s as shown in Figure 2.

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 contents

2) While they were reading, their reading speed was measured as the number of words they could read in 15 s. The viewing distance between the eyes and the device was measured during reading.

3) After reading, the participants evaluated readability for each display by using the visual analogue scale (VAS) shown in Figure 3. They converted the VAS to points between 0 and 100. If they felt that readability was the worst, they marked the left edge of the scale as 0. If they felt that readability was the best, they marked the right edge as 100. It can be considered that VAS = 50 is appropriate for a split decision line (an allowable limit of readability) in this subjective assessment.



Key

1 worst

2 best

Figure 3 — Visual analogue scale (VAS)

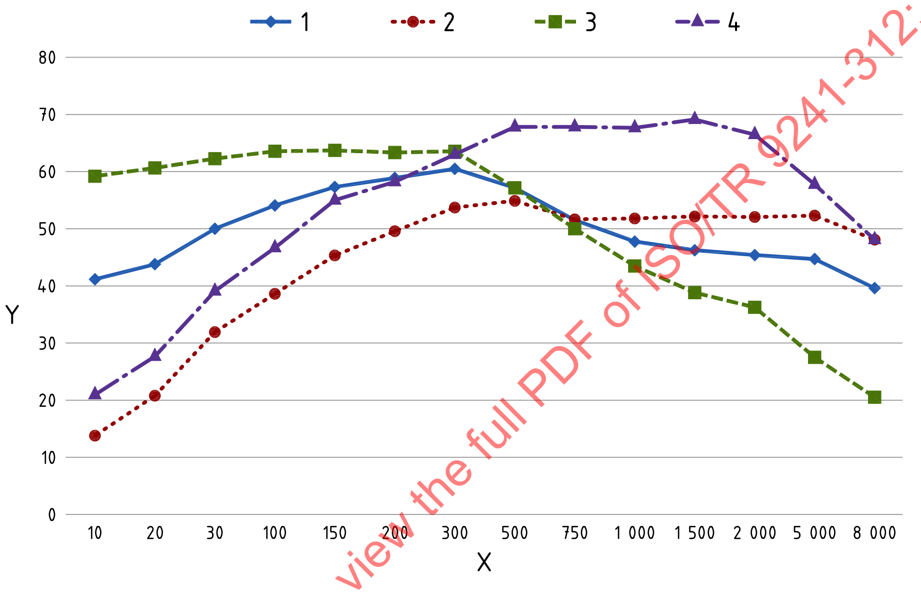
6.3 Experimental results

VAS is a subjective assessment for readability. Figure 5 shows the number of words read aloud by the participants and Figure 6 shows the viewing distance for each display. After reading, the participants evaluated readability for each display by using VAS shown in Figure 4.

6.4 Discussion

1) Participants' evaluation of readability (Figure 4)

ILU-EPD can provide readability under low illuminance conditions in comparison with EPD, backlit LCD, and conventional paper text. Under conditions of illuminance of less than 300 lx, the participants evaluated ILU-EPD significantly higher than EPD. The ILU has a profound effect on readability under low illuminance conditions. However, under conditions of illuminance of more than 750 lx, the participants evaluation of ILU-EPD was worse than EPD. This is an interesting result to investigate in detail in the future.



Key

X illuminance, lx

Y subjective evaluation

1 ILU-EPD

2 EPD

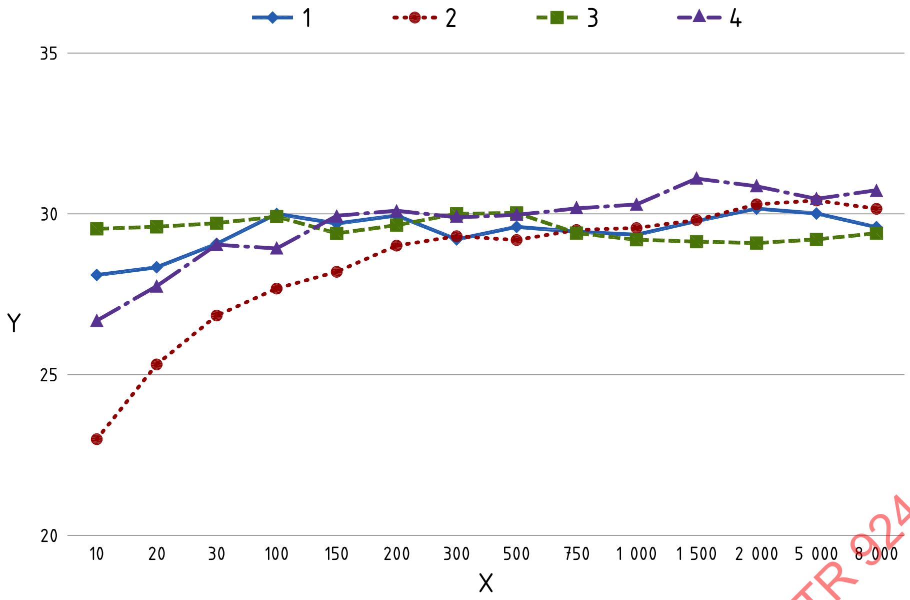
3 LCD

4 paper

Figure 4 — Participants' evaluation

2) Reading speed (Figure 5)

Differences in reading speed were observed at illuminance levels below 200 lx. Here, the lowest reading speed was with the EPD. The use of an ILU considerably improved reading speed with EPD. Below 200 lx, the order of the 4 devices in terms of reading speed (Figure 5) was almost the same as in terms of subjective readability (Figure 4). At illuminance levels above 300 lx, the reading speeds converged to approximately 30 words in 15 s. These results did not correspond to the subjective evaluation, but indicated the minimum illuminance for comfortable reading can be 300 lx.



Key

X illuminance, lx

Y reading speed, in words per 15 seconds

1 ILU-EPD

2 EPD

3 LCD

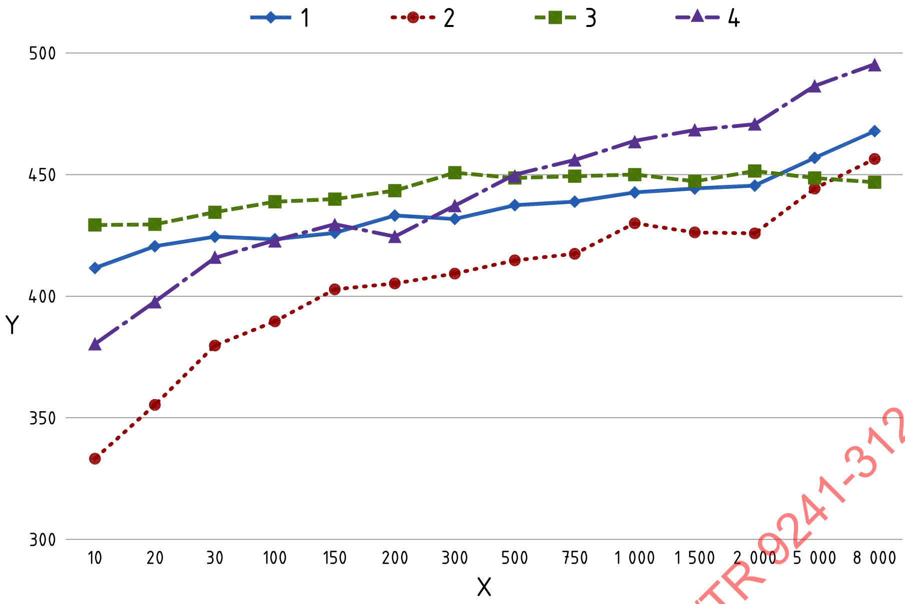
4 paper

Figure 5 — Reading speed

3) Viewing distance (Figure 6)

In terms of the viewing distance as an objective index of evaluation, it was supposed that the viewing distance would be shorter as the text becomes more difficult to be read. The results did not correspond to the subject's evaluation, but indicated that the comfortable viewing distance for reading can be 45 cm.

The above results showed that significant differences exist between ILU-EPDs and EPDs without ILU. The ILU improves readability.



Key

X illuminance, lx
Y viewing distance, mm

1 ILU-EPD
2 EPD
3 LCD
4 paper

Figure 6 — Viewing distance

7 Proposing a baseline setup for readability using VAS evaluation

7.1 General

This study focused on the correlation between the subjective evaluation of readability using a VAS, and reading efficiency measured as reading speed in words per 15 seconds. The methodology for measuring subjective readability and reading speed was described in Clause 5. The correlation analysis included data from illuminance levels between 10 lx and 5 000 lx. A baseline for readability was established at a VAS value of 45 instead of 50[23].

7.2 Experimental condition

7.2.1 Equipment

a) 6-inch ILU-EPD

b) 9,7-inch EPD

c) 9,7-inch backlit LCD

d) conventional paper as a reference (whiteness 69 % copy paper)

7.2.2 Participants

a) Number: 110

b) Gender: male (56), female (54)

c) Age: from 19 to 86 (mean: 45,7, SD: 17,8)

7.2.3 Illumination condition

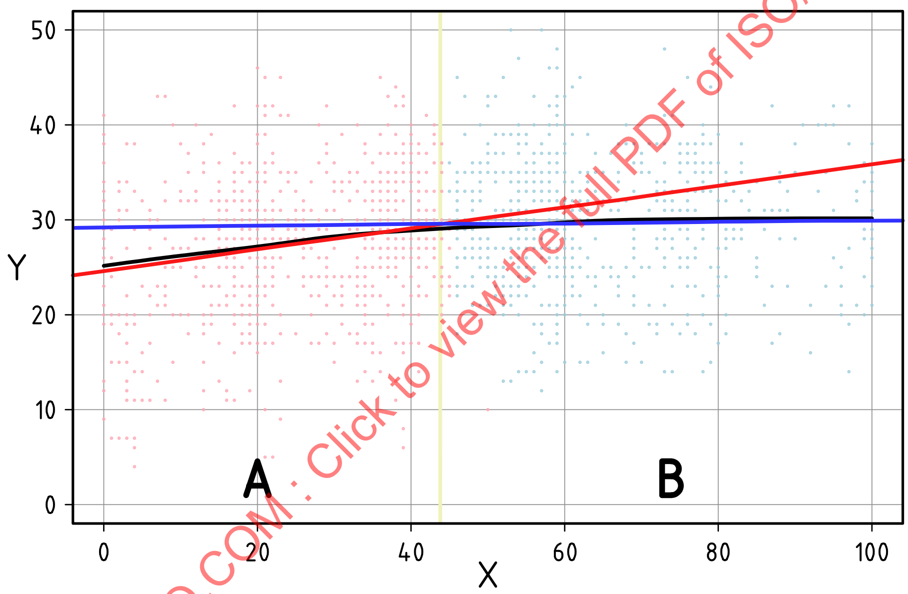
General illumination conditions including illumination light source and viewing geometry were as explained in 6.2.3. The illumination conditions were between 10 lx and 5 000 lx.

7.2.4 Task (Evaluation methods)

The participants had to evaluate the readability of the text (Figure 2) by using VAS as shown on Figure 3.

7.3 Experimental results

This was an evaluation of a VAS baseline. Figure 7 shows that the data were divided into two groups. The first group falls below the baseline (group A). The second group exceeds the baseline (group B). Figure 7 shows the scatter plot and linear regression line of each group. The red dots represent group A, the blue dots represent group B. According to the analysis, the borderline between group A and group B is approximately 45. Furthermore, the regression lines of each group show a consistent regression curve, and the two lines intersect at about 44. From these analyses, the real baseline was found at VAS = 45 not VAS = 50 and this baseline is useful for future investigations concerning the readability of EPD by using VAS.



Key

X VAS

Y reading speed, in words per 15 seconds

A group A

B group B

Figure 7 — Scatter plot of reading speed (in words per 15 seconds) vs. VAS of readability, and regression curve by k-means clustering (*N* = 1 533, *K* = 2)

7.4 Discussion

In this study, an experiment to evaluate the readability of EPD was carried out. Participant evaluations were conducted using a VAS while also checking the participants reading speeds. It was found that it is possible to establish a baseline at VAS value of 45 for future studies to indicate whether participants reach a sufficient level of reading of a text.

8 Verification of the minimum illuminance for readability of an EPD

8.1 General

The aim of this experiment was to verify the minimum illumination for readability with EPD in low illumination (300 lx or less). A participant's readability score and viewing distance were used to evaluate readability. Results show the 200 lx illuminance level as the minimum optimum limit of a comfortable environment for reading with EPD[24][30].

8.2 Experimental condition

8.2.1 Equipment

a) 9,7-inch EPD (150 ppi)

b) 11,5-inch EPD (300 ppi)

c) 9,7-inch backlit LCD

d) conventional paper as a reference (whiteness 69 % copy paper)

8.2.2 Participants

a) Number: 130

b) Gender: male (69), female (61)

c) Age: from 17 to 85 (mean: 45,9; SD: 19,7)

8.2.3 Illumination condition

Illumination in 6 steps (10 lx, 20 lx, 50 lx, 100 lx, 200 lx, 300 lx). These illumination conditions including illumination light source and viewing geometry were as explained in 6.2.3.

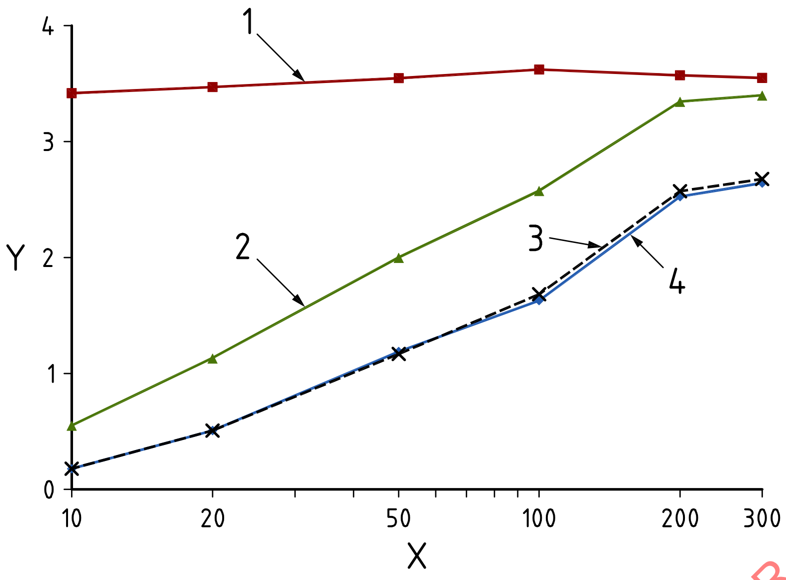
8.2.4 Task (Evaluation methods)

The text which the participants read is a fairy tale written in Japanese with 9-point (3,18 mm in height) Shuei Mincho. There were 34 characters per line, and 13 lines in each text passage. The capability of text interpretation is a level which a fifth grader (almost 11-year-old pupils) in an elementary school can read. The participants read the text displayed on the devices. Subjective evaluations and viewing distances were measured. The evaluation by the participants fell into 6 groups rated between 0 and 5. 0 indicates "very hard to read" and 5 indicates "very easy to read".

8.3 Experimental results

1) Participants assessment score (Figure 8)

The ratings on readability of the backlit LCD was high while the ratings for the EPD was lower. This is because the contrast ratio (luminance contrast) of the EPD was low. Therefore, in this experiment, they aimed to verify the practical allowable lower limit of environment illuminance for reading the EPD in lower conditions of light (less than 300 lx).



Key

X illuminance, lx

Y subjective evaluation, rated between 0 and 5

1 LCD

2 paper

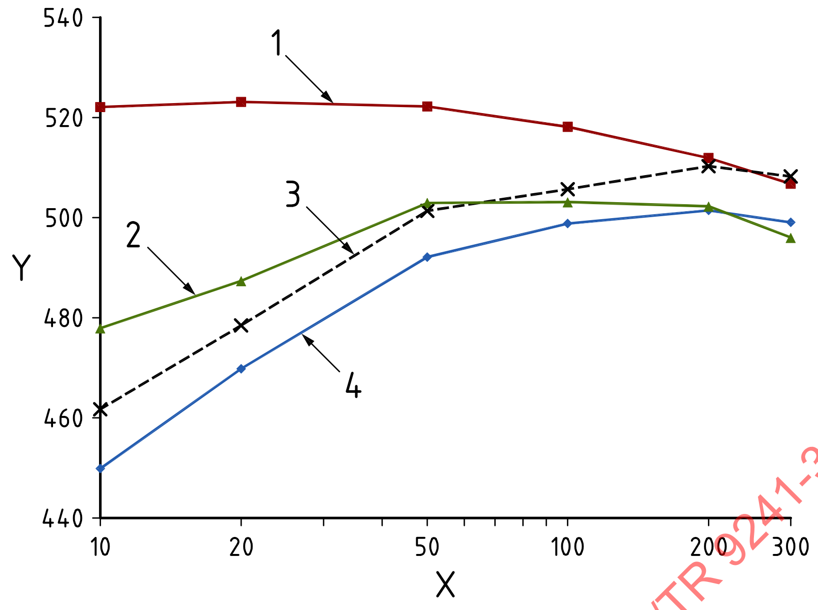
3 EPD (300dpi)

4 EPD (150 dpi)

Figure 8 — Subjective evaluation

2) Viewing distance (Figure 9)

As levels of illuminance increased, the participants moved their heads closer to the LCD. In contrast, participants using the paper and the EPD, moved further away when levels of illuminance were increased. Thus, it was suggested that paper and EPD had an advantage under a brighter environment. In a dark environment, the LCD obtained a good rating for readability, but the participants rated it poorer as illuminance increased. Conversely, the evaluation of the EPD and paper recorded poor ratings in a dark environment but had improved ratings as the environment became brighter. In totality, the viewing distance for all the media forms were similar under between 200 lx and 300 lx illuminance.



Key

X illuminance, lx

Y viewing distance, mm

1 LCD

2 paper

3 EPD (300 dpi)

4 EPD (150 dpi)

Figure 9 — Viewing distance

8.4 Discussion

From the experiment, 200 lx can be a critical illuminance point. Furthermore, in a 200 lx environment, the viewing distance for the EPD was similar to that of the backlight LCD and the paper. Thus, the 200 lx illuminance level is considered the minimum optimum limit of a comfortable environment for reading EPD. As for ILU-EPD, they can compensate for the disadvantages of EPD in lower conditions of light.

9 Contribution of character sizes to the readability of mobile devices

9.1 General

The readability of EPD and backlight LCD have been investigated. This study focused on the contribution of character size to the readability. The study showed that significant differences existed among the devices[25].

9.2 Experimental condition

9.2.1 Equipment (specimen)

a) 9,7-inch EPD

b) 9,7-inch backlit LCD

c) conventional paper as a reference (whiteness 69 % copy paper)

9.2.2 Participants

a) Number: 107

b) Gender: male (49), female (58)

c) Age: from 15 and 78 (mean: 47,6, SD: 15,4)

9.2.3 Illumination condition

The illumination was under 942 lx and viewing distance was kept as 40 cm. The other illumination condition was as explained in 6.2.3.

9.2.4 Task (Evaluation methods)

The reading devices were placed in compartments on desks (Figure 1). There were 30 characters per line in English, and 14 lines in each text passage, as shown in Figure 10. The character fonts were 8 point (2,82 mm in height), 12 point (4,23 mm in height), and 16 point (5,64 mm in height) using the Courier typeface. This display form conforms to those used in the evaluation criteria of a liquid crystal display according to ISO 9241-304[34].

The headrest for the participant's forehead in the compartment was kept at a visual distance of 40 cm. The participants began to read from the top left-hand corner. They recorded the number of capitals Ms that each participant identified in the reading, and the total time the participants needed to read the text was measured. After reading, they evaluated the readability by using VAS to convert into a scale ranging from 0 to 100 points as explained in 6.2.4.

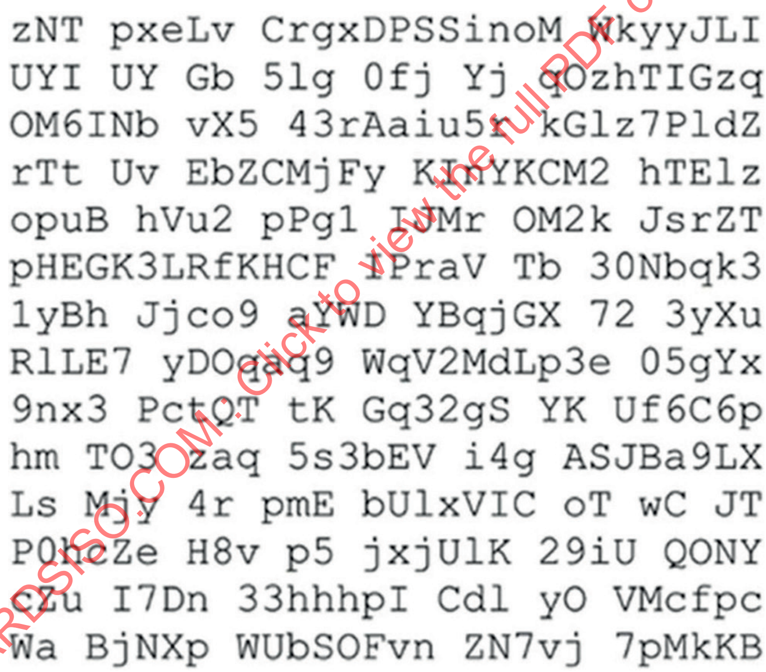
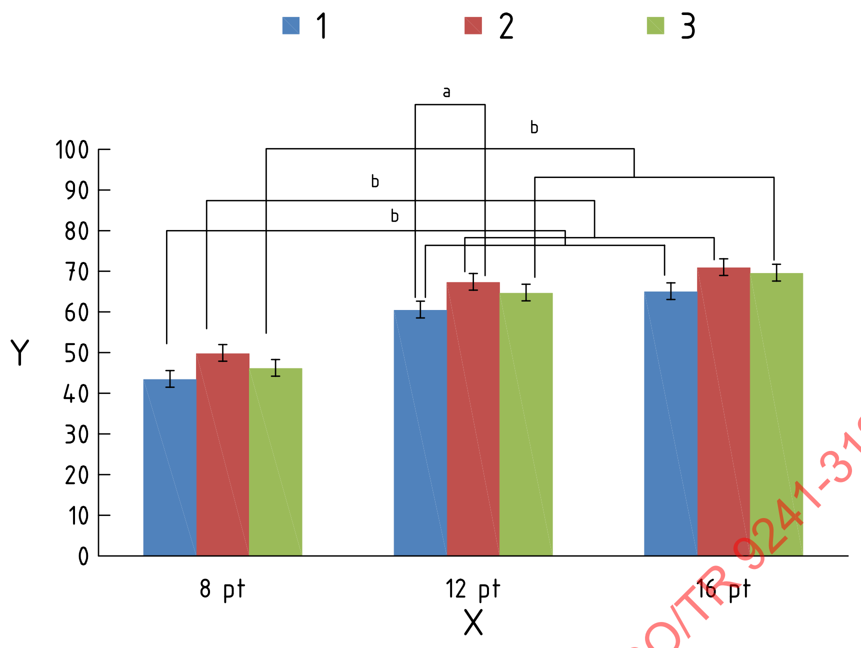


Figure 10 — Example of contents

9.3 Experimental results

Figure 11 shows the participants' evaluation for each device. The participants evaluated the 8-point (2,82 mm in height) font size significantly less than for the 12-point (4,23 mm in height) and 16-point (5,65 mm in height) with the EPD, the LCD and the paper ($p < 0{,}01$). A significant difference was found among the devices for 12-point (4,23 mm in height) between the EPD and the LCD ($p < 0{,}05$).



Key

X character sizes, point

Y subjective evaluation of VAS

1 EPD

2 LCD

3 paper

[a] It is the significant difference in $p < 0,05$.

[b] It is the significant difference in $p < 0,01$.

Figure 11 — Participants' evaluation for each device

9.4 Discussion

The readability of the EPD and the backlight LCD were investigated by focusing on the contribution of character size. There were statistically significant differences between the 8-point size characters (2,82 mm in height) and the 12-point (4,23 mm in height) and 16-point (5,65 mm in height). This study also showed that, statistically, significant differences exist among the EPD and the LCD at 12 points (Figure 11). From the viewpoint of readability, the minimum font size is 8 points (2,82 mm in height) because this is coincident with VAS = 45. The VAS of 12 points (4,23 mm in height) was 60,7 and the VAS of 16 points (5,65 mm in height) was 65,2 of the EPD.

It is interesting that this result in the case of alphabetical font is close to that of Japanese fonts which are used in Japanese paperback books or pocket books, although those typefaces are more complicated than that of alphabetical fonts. This size for Japanese paperbacks is attributed to traditional efforts, that is, trial and error, of making page layouts to satisfy the readers' requirements for comfortable reading.

10 Difference in readability of the contrast ratio of mobile devices

10.1 General

In this study, the effects of the contrast ratios (luminance contrast) of characters and background greyscale were focused on the readability of EPD. The experiments were carried out with a reading test to evaluate the readability of EPD under various contrast ratios. Two types of EPD were used. By way of comparison, conventional paper texts were used[26].

10.2 Experimental condition

10.2.1 Equipment

a) 6-inch ILU-EPD

b) 6-inch EPD

c) conventional paper as a reference (whiteness 69 % copy paper)

The participants used two types of EPD, that is, 212 dpi ILU-EPD and 150 dpi EPD. Texts on the conventional paper printed by PPC were also used.

Since these three devices had different coloured bezel around their screens, each bezel was covered with white Kent paper. Each device was put in the same position in the compartment.

10.2.2 Participants

a) Number: 107

b) Gender: male (49), female (58)

c) Age: from 15 to 78 (mean: 46,9, SD: 15,5)

10.2.3 Illumination condition

The illumination was done at 754 lx using a 6 500 K LED light source to compensate fluorescent lamps and maintain the same colour and temperature. The reason for selecting 754 lx as illumination is shown in Figure 4. The other illumination conditions are as explained in 6.2.3.

10.2.4 Task (evaluation methods)

The display format conformed to those used for evaluation of electronic display devices according to ISO 9241-304[34].

The experimental task was a reading test using random alphanumeric text. The font type was Courier, and the font size was set at 8 points (2,82 mm in height). The contrast ratios were set in three stages by using three background greyscales of 15 (white), 9 (light grey) and 3 (dark grey) along a continuous scale of the 16 steps from 0 (black) to 15 (white). The contrast ratio (luminance contrast) was labelled as "high", "medium" or "low" (Table 2).

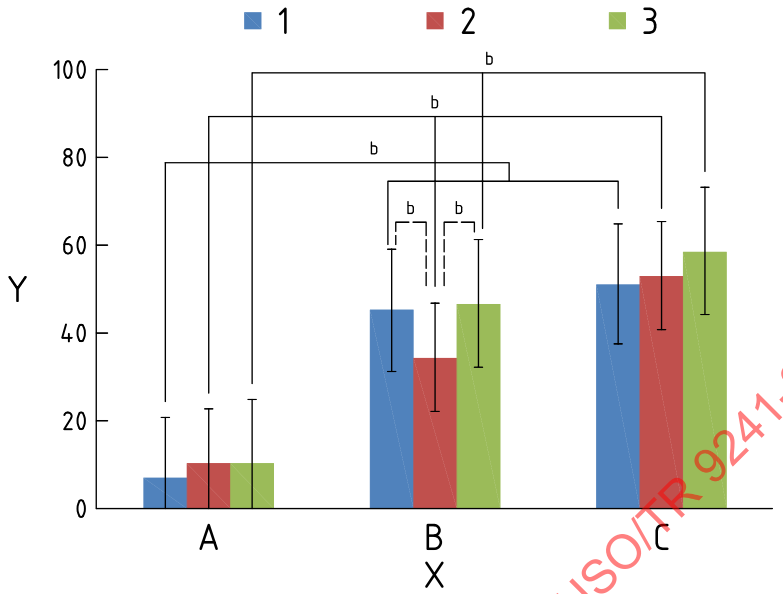
The participants started to read the text from the top left-hand corner. They recorded the number of capital Ms identified in the reading and the total time to read through the text. After reading, the participants evaluated the readability of the text. They evaluated the readability by using VAS to convert into a scale ranging from 0 to 100 points as explained in 6.2.4.

Table 2 — Contrast ratios (luminance contrast)

Item	Low	Medium	High
212 dpi ILU-EPD	2,37	5,36	9,44
150 dpi EPD	1,83	4,38	9,01
Paper	1,31	6,62	14,37

10.3 Experimental results

Figure 12 shows a graph of the participants' evaluations of each device according to the three contrast ratios (luminance contrast). For all the devices, the evaluations decreased significantly between the low and medium contrast ratios (luminance contrast). After applying an ANOVA, the evaluations for the EPD and paper showed significant differences (p < 0,01) in all cases. For the ILU-EPD, there were significant differences (p < 0,01) in two cases (low–medium and low–high).

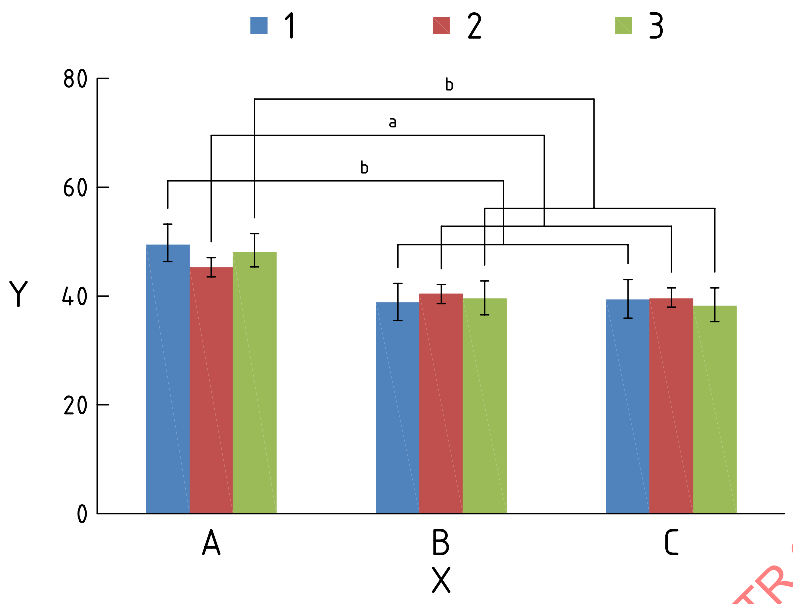


Key

X	contrast ratio (luminance contrast)	A	low contrast ratio
Y	subjective evaluation of VAS	B	medium contrast ratio
1	ILU-EPD	C	high contrast ratio
2	EPD		
3	paper		
b	It is the significant difference in p < 0,01.		

Figure 12 — Participants evaluations for each device

Figure 13 shows a graph of the participants' reading time. There were significant differences for all devices in two cases (low–medium, low–high contrast ratios).



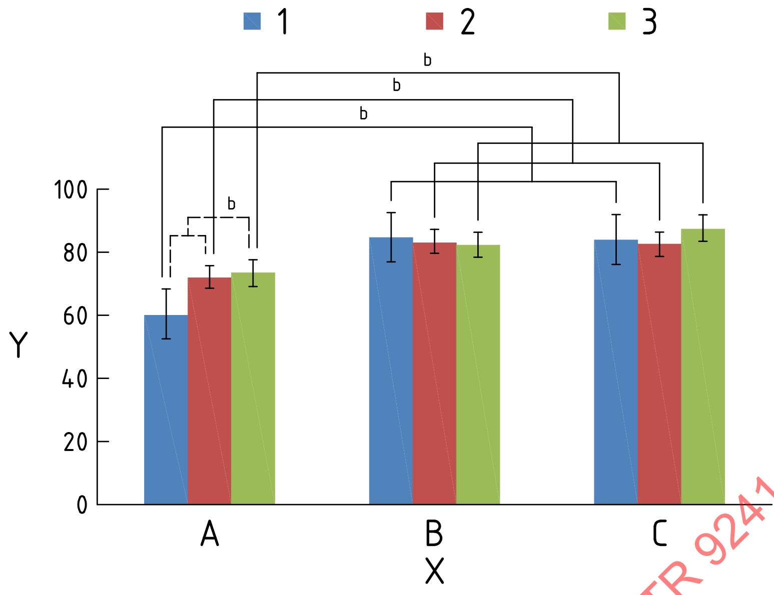
Key

X luminance contrast ratio
Y reading time, seconds
1 ILU-EPD
2 EPD
3 paper
a It is the significant difference in $p < 0{,}05$.
b It is the significant difference in $p < 0{,}01$.

A low contrast ratio
B medium contrast ratio
C high contrast ratio

Figure 13 — Participants' reading time for each device

Figure 14 shows a graph of the percentage of correct answers for each device. There were significant differences ($p < 0{,}01$) for all devices in two cases (low–medium, low–high contrast ratios). In the case of the low contrast ratios (luminance contrast), the percentage of correct answers was lowest. Compared with other devices, the correct answer rate for the ILU-EPD was much lower at the low level of contrast ratio. For the ILU-EPD and EPD, the rate of correct answers was slightly higher at the medium level compared to the high contrast ratio (luminance contrast).



Key

X luminance contrast ratio

Y percentage of correct answers, %

1 ILU-EPD

2 EPD

3 paper

b It is the significant difference in $p < 0,01$.

A low contrast ratio

B medium contrast ratio

C high contrast ratio

Figure 14 — Percentage of correct answers for each device

In Table 2, the contrast ratio (luminance contrast) of the EPD was lowest comparing to those of ILU-EPD and the paper in the medium level. This was similar to the result of the participants' evaluation (Figure 12) because the VAS of the EPD was lowest. At high level, the contrast ratio (luminance contrast) of paper text was higher than ones of both the EPD and the ILU-EPD. This was also similar to the result of the participants' evaluation because the VAS of the paper text was higher than those of the others.

10.4 Discussion

In the case of the medium level of the contrast ratios (luminance contrast), the participants' evaluations of the EPD were lower than those of the other two devices. This is because the contrast ratio (luminance contrast) of the EPD was lower than that of the other devices at the medium level. For the high contrast ratios (luminance contrast), the participants' evaluations for the paper text were higher than those of the other two devices. This is because the contrast ratio (luminance contrast) of paper was higher than that of the other devices at the high level. For all contrast ratios (luminance contrast), the subjective evaluation of paper was higher than that of the ILU-EPD. These results were consistent with previous experiments.[23] For the ILU-EPD and the EPD, the participants' evaluations at the high level were higher than that of the medium level. However, there were no significant differences in the percentage of correct answers. When the contrast ratio (luminance contrast) was between 5 and 10, the readability of the text did not change greatly which was also consistent with the results of previous experiments.[35] Regardless of the type of device, there were some participants who could not read characters at the low level because the background colour was too dark.

Based on these experiments, the necessary, or minimum required, contrast ratio (luminance contrast) for reading would be 5,0.

11 Effects of long-term reading on visual functions and subjective symptoms

11.1 General

This study carried out an experiment of long-term reading. Visual functions and registered subjective symptoms were measured. To verify the effects of fatigue, the objective values such as FVA (functional visual acuity) can be measured. EPDs and backlit LCDs were used, but no significant differences were observed between these devices[28].

11.2 Experimental condition

11.2.1 Equipment

a) 6 inch ILU-EPD

b) 9,7 inch backlit LCD

11.2.2 Participants

a) Number: 10

b) Gender: male (9), female (1)

c) Age: from 21 to 48 (mean: 28,0, SD: 9,9)

11.2.3 Illumination condition

The illumination was 783 lx. The reason for selecting the illumination is shown in Figure 4. The other illumination conditions are as explained in 6.2.3.

11.2.4 Task (Evaluation methods)

The long-term reading experiments in the indoor room were performed with an illuminance of 783 lx. In the experiments, an ILU-EPD display and a tablet PC (LCD) were used. The participants read the text displayed on one of these devices silently. The experiments used two devices and were conducted on two different days separately.

The experimental task for the participants was to read the novel displayed on the devices. There were 35 Japanese characters per line, and 12 lines on each page. The character font was 9 points (3,18 mm in height) using “Hiragino Kaku Gothic (Pro W3)”. The participants read the text for 15 min and 4 periods, a total of 1 h. These documents were different from each other. The participants were asked to answer questionnaires concerning fatigue symptoms. The questionnaires consisted of one statement on general fatigue and 6 statements on visual discomfort, as follows:

— “Do you feel general fatigue?”;

— “Q1: I feel eye strain”;

— “Q2: My eye lids are heavy”;

— “Q3: My eyes feel dry”;

— “Q4: I have burning eyes”;

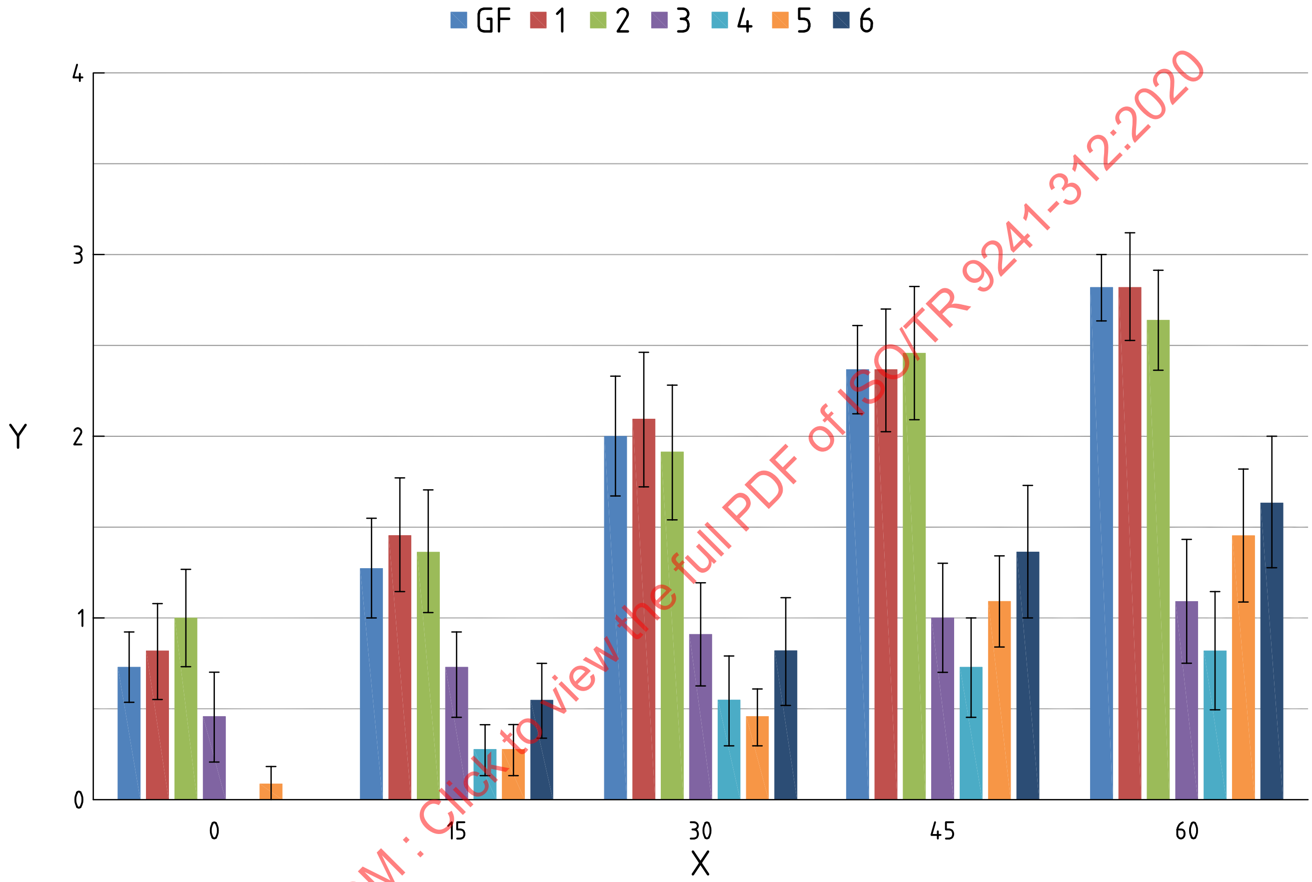
— “Q5: I have a headache”; and

— “Q6: I have difficulty in seeing”.

The participants answered a questionnaire, using a 6-point Likert scale, between “0: I feel no fatigue” and “5: I feel severe fatigue”.

11.3 Experimental results

Figure 15 shows the results of the participants evaluations for the ILU-EPD display, and Figure 16 shows the results of the participants evaluations for the LCD display. The vertical axis shows the degree of symptoms in participants, and the horizontal axis shows the elapsed time. All participants felt increased fatigue with time. The participant statements regarding visual discomfort, such as “Q1: I feel eye strain” and “Q2: My eye lids are heavy” were relatively higher compared to the other visual discomforts. There were no significant differences between the devices.



Key

X time, minutes

Y subjective symptoms, scored 0 to 4

GF general fatigue

1 Q1: I feel eye strain

2 Q2: My eye lids are heavy

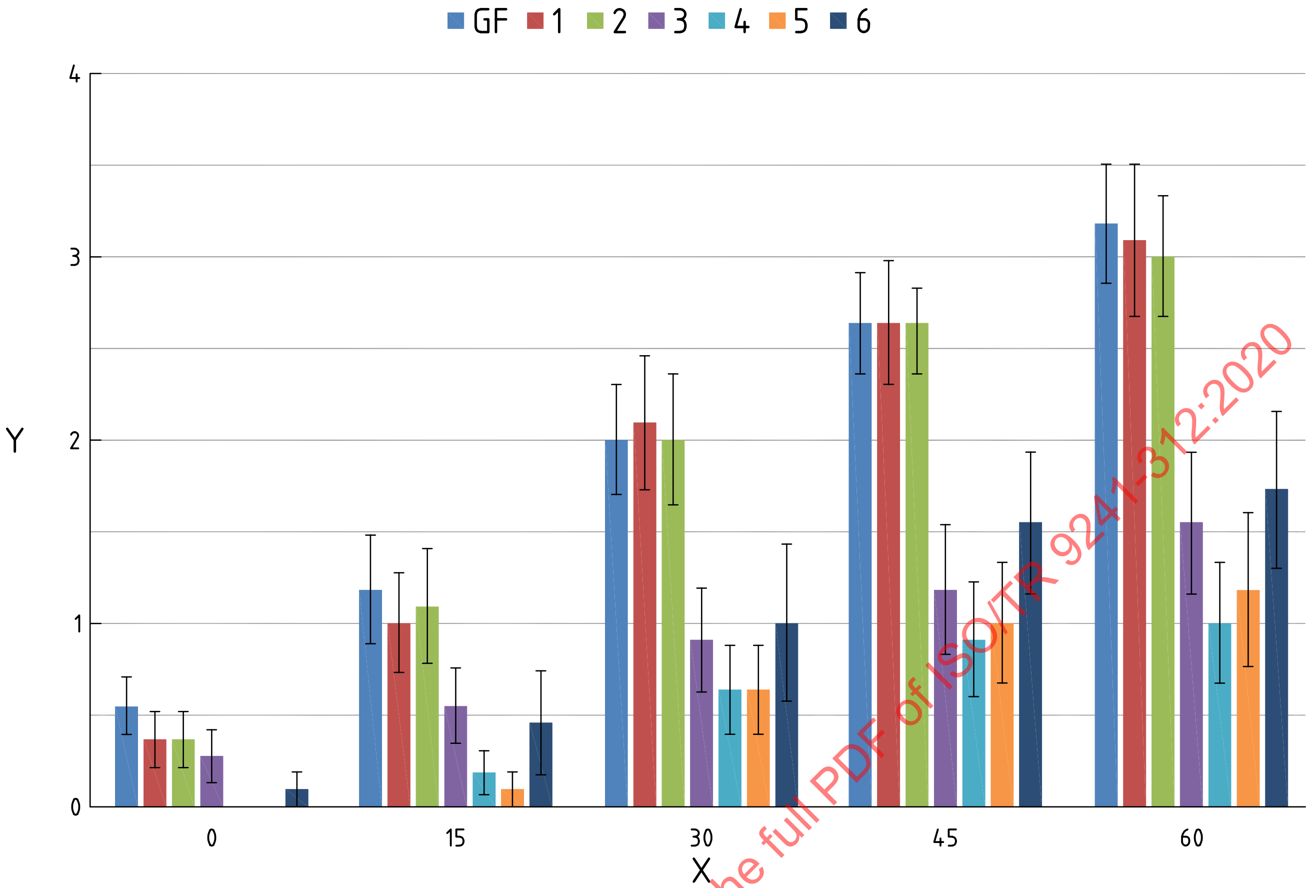
3 Q3: My eyes feel dry

4 Q4: I have burning eyes

5 Q5: I have a headache

6 Q6: I have difficulty in seeing

Figure 15 — Subjective symptoms for ILU-EPD



Key

X time, minutes

Y subjective symptoms, scored 0 to 4

GF general fatigue

1 Q1: I feel eye strain

2 Q2: My eye lids are heavy

3 Q3: My eyes feel dry

4 Q4: I have burning eyes

5 Q5: I have a headache

6 Q6: I have difficulty in seeing

Figure 16 — Subjective symptoms for LCD

11.4 Discussion

From the results, the effects of long-term reading on the participant's fatigue was found to be higher with increasing reading time. To verify the effects, objective values such as functional visual acuity (FVA) are needed. In this experiment, no significant difference was observed between the ILU-EPD and the backlit LCD.

12 Evaluation of readability for tablet devices by the severity of cataract cloudiness

12.1 General

This study carried out experiments with a reading test to evaluate the readability of tablet devices and EPDs under various illuminance conditions by people in age groups with cataract. As a result, there were significant differences between high and low cloudy cataracts in readability. There is also a correlation between each amount of cloudiness with cataract and each age group[29].

12.2 Experimental condition

12.2.1 Equipment

a) 6-inch ILU-EPD

b) 9,7-inch backlit LCD

12.2.2 Participants

a) Number: 99

b) Gender: male (49), female (50)

c) Age: from 18 to 81 (mean: 46,2, SD: 16,8)

Tables 3 and 4 show how the participants were placed into groups.

Table 3 — Age groups of participants

Name	Age range	Number of people	Average age	Standard deviation
Young	18-44	37	28,4	7,5
Middle	45-64	44	50,8	4,2
Elderly	65-81	18	71,8	4,1

Table 4 — Cataract groups

Name	Cataract range	Number of people	Average cloudiness	Standard deviation
Low cloudy cataract	0–99	71	64,4	19,5
Middle cloudy cataract	100–149	17	119,4	13,5
High cloudy cataract	150–255	11	169,4	14,8

12.2.3 Illumination condition

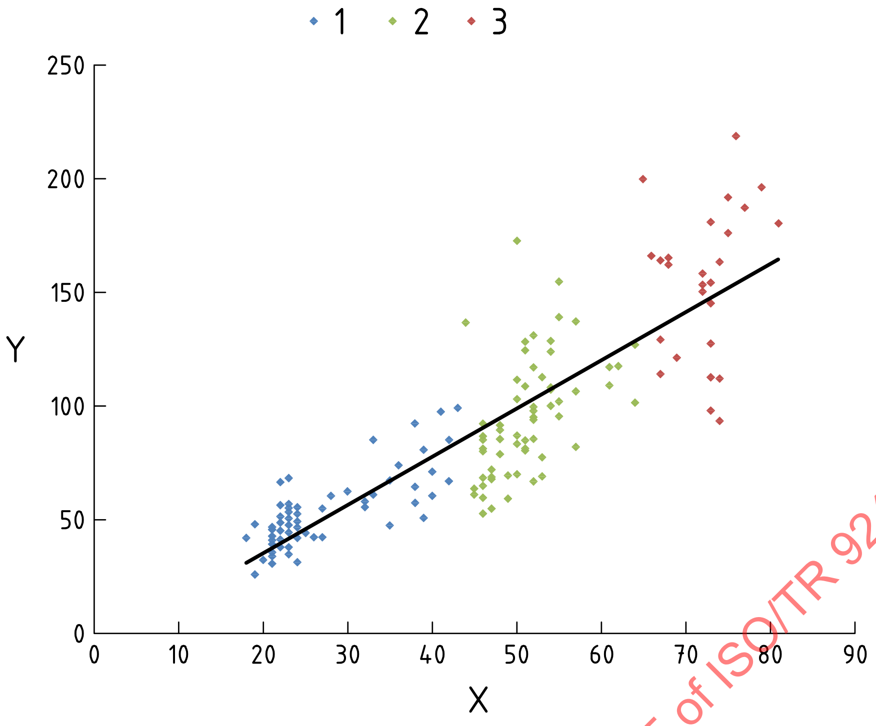
The illumination was set at 10 levels (10 lx, 100 lx, 200 lx, 300 lx, 500 lx, 750 lx, 1 500 lx, 2 000 lx, 5 000 lx, 10 000 lx), and other conditions are explained in 6.2.3.

12.2.4 Evaluation methods

Each subject was tasked with reading the text displayed on a device. There were 5 English words per line and 10 lines in the text. The subjects were given 15 s to read each text. After reading, the subjects evaluated the readability of the device by using VAS as shown in Figure 3. The experiments were conducted in a compartment shown in Figure 1 in a darkened room. In order to adjust to constant illumination, fluorescent lights and an LED (colour temperature: 6 500 K) with a light diffuser was used.

12.3 Experimental results

Figure 17 shows the amount of cloudiness due to cataracts by age group. The data was analysed for each of 3 groups based on the rate of the degree of cloudiness in each of the participants' eyes.



Key

X age, in years

Y degree of cloudiness

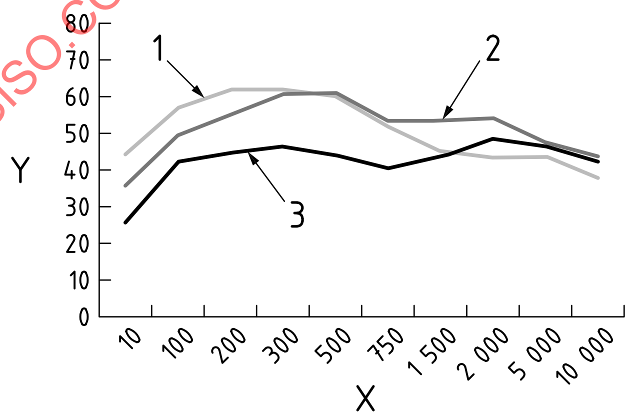
1 age from 18 to 44

2 age from 46 to 64

3 age from 65 to 81

Figure 17 — Amount of cloudiness with cataracts

Figure 18 shows the participants' evaluation by each cataract group for the ILU-EPD. Under conditions of low illuminance, it was found that the participants with lower levels of cloudiness were evaluated with good vision while those with high cloudiness had poor vision. However, under conditions of high illuminance, the subjective evaluations of those individuals with high cloudy cataracts was better than that of those with low cloudy cataracts.



Key

X illuminance, lx

Y participants' evaluation of VAS

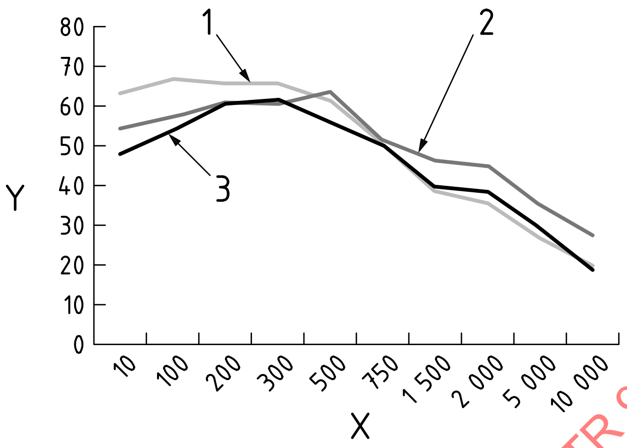
1 cataract range from 0 to 99

2 cataract range from 100 to 149

3 cataract range from 150 to 255

Figure 18 — Participants' evaluation of each cataract group for the ILU-EPD

Figure 19 shows the participants' evaluation of the LCD for each level of cloudiness. Under conditions of more than 200 lx, there were no significant differences between those with high and low cloudy cataracts. Under conditions of low illuminance, those with high cloudy cataracts were worse. Under conditions of high illuminance, the participants evaluation was similar to high and low cloudy cataracts.



Key

X illuminance, lx

Y participants' evaluation of VAS

1 cataract range from 0 to 99

2 cataract range from 100 to 149

3 cataract range from 150 to 255

Figure 19 — Participants' evaluation of each cataract group for the LCD

12.4 Discussion

The number of mobile devices has increased rapidly in recent years and such devices are used by both young and old. Compared to the young, the elderly are more likely to suffer from cataracts.

The readability of the LCD and ILU-EPD for each group rated by the amount of cloudiness with cataracts was evaluated. It was reasserted that the higher the cloudiness with cataracts, the poorer the vision.

As the results show, under low conditions of illuminance, i.e. less than around 200 lx, the subjective evaluations for the LCD and ILU-EPD ranked in descending order according to the degree of cloudiness (from low to high). Therefore, under conditions of low illuminance, the participants with a high degree of cloudiness are generally estimated to have the poorest vision, and those with low cloudiness had the best vision among these three grades. The evaluations show that persons with little cloudiness (around 40) can read well on the devices until about 10 000 lx. Then, increasing illuminance made them feel glare and disturbed their reading. The reading test in this study evaluated the readability of tablet devices and EPDs under various conditions of illuminance with participants grouped according to their cataract levels. There were significant differences between high and lower levels of cloudiness with cataracts. There is a correlation between each amount of cloudiness with cataracts and each age group. This suggests that it is important not only to take age (age-related eye focusing) but also the amount of cloudiness in cataracts into account when developing such reading devices.

13 Summary

A series of results from 7 experiments with electrophoretic displays with a total of 673 participants led to the following points, as to the use of electrophoretic displays.

1) For a viewing distance in the range between 400 mm and 450 mm, the preferred luminance contrast was larger than 5, and the preferred Courier font size was larger than 8 points (2,82 mm in height), both on the screen.

2) The participants score of ease of reading increased with illuminance level and reached the critical score, changing from “hard to read” to “easy to read” at the illuminance of 200 lx

3) Fatigue increased with reading time, which was not influenced by the display used, such as ILU-EPD or LCD.

4) According to the participants’ comprehensive evaluation, ILU-EPD has a positive effect on enhancing readability.

5) For illuminance levels below 200 lx, increasing cataract-related cloudiness decreased readability on both EPDs with ILU and backlit LCDs. For illuminance levels above 200 lx up to 10,000 lx, no significant effect of cloudiness on readability was found. Readability on backlit LCD generally decreased with increasing illuminance.

14 Context of use for electrophoretic displays

There are many variables which contribute to, and define, the context of use for EPD. Those can include users, tasks, postures, environments and equipment. Users tend to use EPD for reading, monitoring, controlling and observing. Postures can include lying down, sitting, standing, reclining, walking and running. Table 5 shows the ISO and JIS standards covering illuminance requirements for the following 10 work environments:

1) residence;

2) general buildings;

3) school buildings;

4) hospital wards;

5) commercial facility;

6) institutions;

7) place of entertainment;

8) transportation facilities;

9) outdoor public space;

10) factories.

In these working environments, users are considered for the most part to be reading, and their posture to be sitting or standing.

Also, illuminance requirements in the field of architecture are covered by ISO and JIS standards. Table 5 shows illuminance levels required in the architecture field.

Table 5 — Illuminance levels required in the architecture field

Area	Working areas	Illuminance lx	Standards
Residence	Living room	200–1 000	JIS Z 9110
	Kitchen	100–300	JIS Z 9110
	Bedroom	20–500	JIS Z 9110
	Den	100–750	JIS Z 9110
	Bathroom	75–300	JIS Z 9110

Table 5 *(continued)*

Area	Working areas	Illuminance lx	Standards
General office building	Entrance	100	ISO 8995 series
	Elevator hall/inside	300/150	JIS Z 9110/ ISO 8995 series
	Reception	300	JIS Z 9110
	Large office	750/500	JIS Z 9110/ ISO 8995 series
	Small office	750/500	JIS Z 9110/ ISO 8995 series
	Archives	200	JIS Z 9110/ ISO 8995 series
	Drawing office	500–750	JIS Z 9110/ ISO 8995 series
School buildings	Classrooms	300–500	ISO 8995 series
	Lecture hall	500	ISO 8995 series
	Teachers room	300	ISO 8995 series
	Laboratory office	500	JIS Z 9110
Hospital wards	Waiting lounge	200	ISO 8995 series
	Pharmacy	1 000	JIS Z 9110
	Consultation room	500	JIS Z 9110
	Wards	100–300	ISO 8995 series
	Operation room	1 000	ISO 8995 series
Commercial facility	Retail store	300–500	ISO 8995 series
	Supermarket	500–2 000	JIS Z 9110
	Departmental store	750–1 000	JIS Z 9110
	Restaurant	200–500	ISO 8995 series
	Kitchen	500	ISO 8995 series
Institutions	Museum	300	ISO 8995 series
	Library	200–500	ISO 8995 series
	Church & Temple	100–300	ISO 8995 series
Place of entertainments	Theatre	200	JIS Z 9110/ ISO 8995 series
	Cinema (Movie)	100	JIS Z 9110
Transportation facilities	Railway station	100–500	JIS Z 9110
	Airport lounge	200	ISO 8995 series
Outdoor public space (no effect from sunlight)	Downtown	20	JIS Z 9110
	Park	20	JIS Z 9110
	Agora, plaza, square	50	JIS Z 9110
	Recreation ground	20–500	JIS Z 9110
	Athletic ground	20–500	JIS Z 9110
Factory	Production line	100–1500	JIS Z 9110
	Control room	500	JIS Z 9110/ ISO 8995 series

Using these illumination conditions under the relevant context of use, EPD may or may not be appropriate.

Tables 6 to 15 show adaptive possibilities for EPD. EPD and ILU-EPD are specified at the end of Clause 5.

Tables 6 to 15 indicate only the space brightness which can provide comfortable reading conditions to the users. They do not include the effects of uncomfortable atmospheric temperature, vibration, noise, and unpleasant direct sunlight which disturb comfortable reading conditions.

Table 6 — Residence

Area	EPD	ILU-EPD
Living room	A	A
Kitchen	A/E	A
Bedroom	A	A
Den	A	A
Bathroom	A/E	A

A Applicable or adequate possibility.

E An external illumination light source should be used.

Table 7 — General buildings

Area	EPD	ILU-EPD
Entrance	E	A
Elevator hall/inside	E	A
Reception	A	A
Large office	A	A
Small office	A	A
Archives	A	A
Drawing office	A	A

A Applicable or adequate possibility.

E An external illumination light source should be used.

Table 8 — School buildings

Area	EPD	ILU-EPD
Classroom	A	A
Lecture hall	A	A
Teachers room	A	A
Laboratory office	A	A

A Applicable or adequate possibility.

E An external illumination light source should be used.

Table 9 — Hospital wards

Area	EPD	ILU-EPD
Waiting lounge	A	A
Pharmacy	A	A
Consultation room	A	A
Wards	A/E	A
Operation room	A	A

A Applicable or adequate possibility.

E An external illumination light source should be used.

Table 10 — Commercial facility

Area	EPD	ILU-EPD
Retail store	A	A
Supermarket	A	A
Department store	A	A
Restaurant	A	A
Kitchen	A	A
A Applicable or adequate possibility.		
E An external illumination light source should be used.		

Table 11 — Institutions

Area	EPD	ILU-EPD
Museum	A	A
Library	A	A
Church & Temple	A/E	A
A Applicable or adequate possibility.		
E An external illumination light source should be used.		

Table 12 — Place of entertainments

Area	EPD	ILU-EPD
Theatre	A	A
Cinema (Movie)	E	A
A Applicable or adequate possibility.		
E An external illumination light source should be used.		

Table 13 — Transportation facilities

Area	EPD	ILU-EPD
Railway station	A/E	A
Airport lounge	A	A
A Applicable or adequate possibility.		
E An external illumination light source should be used.		

Table 14 — Outdoor public space (no effect from sunlight)

Area	EPD	ILU-EPD
Downtown	E	A
Park	E	A
Agora, plaza, square	E	A
Recreation ground	A/E	A
Athletic ground	A/E	A
A Applicable or adequate possibility.		
E An external illumination light source should be used.		