The Effects of Ambient Illuminance and Aging on the Evaluation of the Readability of E-paper

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Abstract We carried out an experiment to evaluate the effects of ambient illuminance and aging on the readability of E-papers. On the basis of this and our prior studies under various illuminance conditions, we suggest that subjective performance declines with decreasing illuminance, and that illuminance of 300 lx is the limiting lighting level at which subjects can maintain their performance. Furthermore, our findings indicate the possibility that subject scores of 45 to 47 on a Visual Analog Scale (VAS) indicate passable readability. With regard to aging, the built-in light sources of backlit LCDs and E-paper contribute to improving subjective evaluations, especially for the elderly group in the lower illuminance conditions. However, the younger groups tended to rate the self-luminescent devices poorly at higher levels of illuminance, suggesting that improvements in these devices are needed for these higher levels of lighting.

Keywords: Illuminance, E-paper, Visual Analog Scale, Aging, Frontlight, Backlit

1. Introduction

The use of e-paper readers has spread remarkably, and appears to be expanding for all ages. It is reported that various factors such as aging, ambient illuminance, and device type effect the readability of e-paper readers¹⁾²⁾. In this study we used a silent reading test to evaluate the readability of e-paper readers under various illuminance levels for different age groups.

2. Methods

2.1 Subjects

The subjects for this study were 58 healthy males and females between the ages of 13 and 82 years (M 46.8, SD 16.6). Subjects who usually wore glasses or contact lenses used them for the experiments. The subjects were divided into four groups by age: 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). The young group had sufficient amplitude of accommodation. The middle-aged group had sufficient

Table 1 Subjects divided into age groups

	Young	Middle	Senior Middle	Elderly	Total
People	12	12	26	8	58

near vision ability, although their accommodation was slightly weak. The senior middle-aged group had mild presbyopia and problems in near vision work. The elderly group had typical presbyopia and generally had to wear near vision glasses. **Table 1** shows the number of subjects divided into age groups. We obtained informed consent from all subjects and approval for the study from the Ethical Review Board of the Graduate School of Information Science at Nagoya University.

2.2 Experimental design

We carried out the experiment under six levels of illuminance (10 lx, 30 lx, 100 lx, 300 lx, 1,000 lx, and 3,000 lx) using a 6500 K LED light source with a fluorescent lamp having a uniform color temperature in a darkened room. The headrest for the subject's forehead, which was on the lighting system, was kept at a visual distance of 40 cm. We created the lightning system with reference to a previous study³⁾. The subjects looked at devices at an angle of about 100 degrees. We put the reading devices into the lighting system placed on a desk (**Figure 1**). We used two types of e-paper, an

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Fig. 1 The setup for reading

Amazon Kindle Paperwhite™⁴⁾ (released in 2013) and a Sony Reader™⁵⁾ (released in 2013) and one type of backlit LCD (Apple iPad⁶⁾). We also used conventional paper text (with the text printed on PPC paper of 69% whiteness) as a reference. Below, we will refer to the Paperwhite as PW, the Sony Reader as SR and the conventional paper as Paper. The PW is an electrophoretic display (EPD) with a front light and the SR is a reflective EPD. In order to avoid any influence from the frame of the media, the subject read from a bezel covered with white Kent paper and only the screen showing. The test media or test paper was mounted on the center of a board. The text displayed on each medium was set at the same height. The front light level of the PW and the back light level of the iPad were set to maximum levels. The text color was black/dark, and the background color was white/bright. **Figure 2-1** and **2-2** show the screen luminance under each illuminance condition. We calculated the contrast ratio from the measured values of the brightness of the background color and text color (**Figure 2-3**).

2.3 Task design

The experimental task was a reading test. We used random alphanumeric text and unified the size of the characters. The font type was Courier, and the font size was set at 8 pt (approx. 2.6 mm height) (**Figure 3**). The display format conformed to that used for evaluation of

Fig. 2-1 The screen luminance of the white/bright background

Fig. 2-2 The screen luminance of the black/dark background

Fig. 2-3 The contrast ratio of each device for given illuminance

electronic display devices by the International Organization for Standardization (ISO)⁷⁾. We had subjects read the text silently from the top left and measured the total time of the procedure. The subjects were asked to count the number capital letter "M"s in the total text with a counter as they read through the characters. We calculated the correct answer rate from

QeILPNAH vV 2FGM d3CBVE PHLeST
 ZM39v2qLYM ZQt fdPZN 7bguS4RyP
 o35 nMkc6 ef Gz8 7HVScokWh7rFN
 RPh FxHY 8nM bN z2hHqM KhQj 9F
 Gilqo 64 MLE0L3 9lgu NJadELEte
 l4I 1LuGKh ty2M pL uT mc vFF3E
 TxQTpe sd2Kk Vk60anjylyU6D rSP
 PB2T8Yq x5 scBKEz32 pw5X nvtYF
 bhXqV NPZ oTPtYUY CXK 5c8M fmo
 sg jp LX uIX3tRpp jfK f4CU oYS
 Wv lbV qRtbz wTr8qP 3wB g99Tu3
 WH6 R9D8ZQKBi x9fc 7bsPzA nm5a
 Ok 2XyemB5u t1 sDk0 j1HhMymxKd
 RjYe JZ txaK 4m SU A7MOTqU06gx

Fig. 3 Example of text for reading task

the number "M"s that the subjects found and the actual number of "M"s. The correct answer rate was not entirely exact because the subjects sometimes misread other alpha characters as "M"s. The reading time and correct answer rate were divided by the average values of each of the subject's actual values to eliminate the influence of the subject's individual ability. We called these two calculations the reading time index and correct answer rate index. The high-scoring reading time index means that it takes the subject a long time to read. The high scoring correct answer rate index means the large number of correct answers. After reading, the subjects evaluated the readability of the texts using a Visual Analog Scale (VAS). We converted the values of the VAS into a 100-point scale in the analysis of subjective evaluation. The high-scoring VAS means the good readability. As we used four kinds of devices and six levels of illuminance, each subject was asked to perform 24 tests. We treated the trials that subjects could not read as missing values. We used one-way analysis of variance (ANOVA) as a statistical method to evaluate our results and we also used the Scheffé multiple comparison procedure.

3. Result

3.1 Screen luminance of each device

Figure 2-1 and Figure 2-2 show a comparison of the screen luminance of white/bright and black/dark background for each illuminance. Both the white/bright and black/dark background screen luminance of the PW, SR and Paper increased as the level of illuminance increased. The screen luminance of the black/dark background of the light-emitting iPad showed little change, while the white/bright of the iPad increased as the level of illuminance went up. Figure 2-3 shows a contrast ratio of each device for a given illuminance. The contrast ratios of the PW, SR and Paper showed little change under the six illuminance levels. The contrast

Table 2-1 Subjects' evaluations using four devices under six ambient illuminance levels

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10lx	33.49 ± 2.95 ^{a,b,c}	12.16 ± 3.16 ^{a,b,c,d}	46.22 ± 2.80	16.73 ± 2.37 ^{a,b,c}
30lx	37.38 ± 2.63	22.22 ± 2.45 ^{e,f,g}	50.10 ± 2.71	27.34 ± 2.69 ^{e,f,g}
100lx	42.41 ± 2.49	29.89 ± 2.22 ^{a,h,i}	51.78 ± 2.40	37.18 ± 2.62 ^{a,h,i}
300lx	46.41 ± 2.36 ^a	37.85 ± 2.27 ^{b,e,j}	55.85 ± 2.53	48.07 ± 2.67 ^{b,e}
1,000lx	49.17 ± 2.26 ^b	48.29 ± 2.34 ^{c,f,h}	55.81 ± 2.86	55.52 ± 2.43 ^{c,f,h}
3,000lx	49.05 ± 2.73 ^c	53.47 ± 2.75 ^{d,g,i,j}	51.76 ± 3.15	58.95 ± 2.63 ^{d,g,i}

† Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

† For example, 10 lx and 300 lx in the PW column are given the letter 'a'. This means that the subjective evaluation of 300 lx condition is significantly better than that of 10 lx

Fig. 4-1 Subjects' evaluations under six illuminance levels

ratio of the iPad obtained the best rating among all the devices; however, it decreased considerably when the luminance increased.

3.2 Evaluations by illuminance levels

Table 2-1 and Figure 4-1 show a comparison of the subjects' evaluation (VAS) for each level of illuminance. The VAS for the SR were the worst under illuminance of lower than 300 lx. The VAS for the PW showed significant differences ($p < 0.05$) between 10 lx and all illuminance conditions more than 300 lx. The VAS for the SR showed significant differences ($p < 0.05$) between 10 lx and all illuminance conditions more than 100 lx and, between 30 lx and all illuminance conditions more than 300 lx and, between 100 lx and more than 1,000 lx and between 300 lx and 3,000 lx. The VAS for Paper showed significant differences ($p < 0.05$) between 10 lx and all illuminance conditions more than 100 lx and, between 30 lx and all illuminance conditions more than 300 lx, and between 100 lx and more than 1,000 lx. No significant differences were observed among the illuminance levels with the iPad, but the evaluations of the iPad were worse than Paper at the illuminance of 3,000 lx. These results were

Table 2-2 The reading time index with four devices under six ambient illuminance levels

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10lx	1.03 ± 0.02 ^a	1.32 ± 0.05 ^{a,b,c,d,e}	0.95 ± 0.02	1.11 ± 0.03 ^{a,b,c,d}
30lx	1.02 ± 0.01	1.10 ± 0.02 ^{a,f,g}	0.95 ± 0.01	1.09 ± 0.02 ^{e,f,g,h}
100lx	1.00 ± 0.01	1.03 ± 0.02 ^b	0.97 ± 0.01	0.99 ± 0.01 ^{a,e}
300lx	0.99 ± 0.01	1.01 ± 0.02 ^c	0.96 ± 0.01	0.96 ± 0.02 ^{b,f}
1,000lx	0.97 ± 0.01 ^a	0.96 ± 0.01 ^{d,f}	0.95 ± 0.01	1.00 ± 0.01 ^{c,g}
3,000lx	0.98 ± 0.01	0.96 ± 0.01 ^{e,g}	0.97 ± 0.01	0.94 ± 0.01 ^{d,h}

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 4-2 The reading time index under six illuminance levelss

similar to those that we obtained in a previous study ²⁾. **Table 2-2** and **Figure 4-2** show a comparison of the reading time index for each illuminance. The reading time index for the PW showed significant differences ($p < 0.05$) between 10 lx and 1,000 lx. The reading time index for the SR showed significant differences ($p < 0.05$) between 10 lx and all illuminance conditions more than 30 lx and between 30 lx and all illuminance conditions more than 1,000 lx. There was no significant difference among illuminance levels for the iPad. The reading time index for Paper showed significant differences ($p < 0.05$) between 10 lx and all illuminance conditions more than 100 lx and between 30 lx and all illuminance conditions more than 100 lx. **Table 2-3** and **Figure 4-3** show a comparison of the percentage of correct answers (the correct answer rate index) for each illuminance. We did not observe significant differences among illuminance levels with any of the devices except for a difference with Paper. The correct answer rate index for Paper showed significant differences ($p < 0.05$) between 30 lx and 1,000 lx and between 1,000 lx and 3,000 lx.

3.3 Subjective evaluation by illuminance level for each age group

We conducted age-specific evaluation of the VAS for

Table 2-3 The correct answer rate index with four devices under six ambient illuminance levels.

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10lx	1.03 ± 0.02	0.93 ± 0.03	0.96 ± 0.03	1.01 ± 0.03
30lx	1.03 ± 0.02	0.98 ± 0.03	1.01 ± 0.02	0.98 ± 0.02 ^a
100lx	1.03 ± 0.02	0.96 ± 0.03	0.93 ± 0.03	1.02 ± 0.02
300lx	1.01 ± 0.02	0.99 ± 0.03	0.93 ± 0.02	1.01 ± 0.02
1,000lx	1.04 ± 0.02	1.00 ± 0.02	0.99 ± 0.02	0.99 ± 0.02 ^b
3,000lx	1.03 ± 0.03	1.01 ± 0.02	1.01 ± 0.02	1.10 ± 0.02 ^{a,b}

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 4-3 The correct answer rate index under six illuminance levels

each illuminance. **Table 3-1** and **Figure 5-1** show a comparison of the young group's VAS for each level of illuminance. No significant differences were observed among the illuminance levels with the PW, SR and iPad. The VAS for Paper showed significant differences ($p < 0.05$) between 10 lx and more than 1,000 lx, and between 30 lx and 3,000 lx. In comparison, the subjects rated Paper better than the SR under the illumination conditions higher than 300 lx, and better than the PW under the illumination conditions higher than 1,000 lx. The evaluation of Paper was the best in the 3,000 lx condition. The difference between the iPad and Paper in the subjects' evaluations under the 3,000 lx illuminance condition tended to be larger in the young group than in the other age groups.

Table 3-2 and **Figure 5-2** show a comparison of the middle-aged group's VAS for each illuminance. There was no significant difference among illuminance levels for the iPad. The VAS for the PW showed significant differences ($p < 0.05$) between 10 lx and more than 1,000 lx, and between 30 lx and more than 1,000 lx illuminance. The VAS for the SR showed significant differences ($p < 0.05$) between 10 lx and more than 1,000 lx, between 30 lx and more than 1,000 lx, and between

Table 3-1 Subjects' evaluations in the Young group using four devices under six ambient illuminance levels

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10 lx	42.17 ± 6.28	16.29 ± 10.49	53.50 ± 4.47	19.20 ± 6.58 ^{a, b}
30 lx	43.00 ± 4.73	27.10 ± 6.98	55.67 ± 4.25	25.40 ± 5.27 ^c
100 lx	42.08 ± 3.97	34.80 ± 5.20	54.75 ± 4.48	32.50 ± 4.45
300 lx	44.83 ± 2.99	38.58 ± 4.25	55.42 ± 5.37	45.67 ± 6.47
1,000 lx	44.00 ± 3.47	44.42 ± 4.81	54.42 ± 6.20	53.42 ± 5.54 ^a
3,000 lx	41.75 ± 4.99	49.17 ± 6.44	45.92 ± 6.36	59.42 ± 6.37 ^{b, c}

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 5-1 VAS of the Young group under six illuminance levels**Table 3-2** Subjects' evaluations in the Middle-aged group using four devices under six ambient illuminance levels.

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10 lx	22.46 ± 1.70 ^{a, b}	5.25 ± 1.71 ^{a, b}	38.42 ± 4.14	13.38 ± 2.40 ^a
30 lx	25.27 ± 1.93 ^{c, d}	18.90 ± 4.46 ^{c, d}	44.67 ± 4.53	29.09 ± 6.92
100 lx	35.00 ± 5.02	27.90 ± 4.18 ^e	48.92 ± 4.71	40.73 ± 6.57
300 lx	41.50 ± 5.27	35.67 ± 4.10	60.83 ± 5.10	45.00 ± 7.87
1,000 lx	48.58 ± 4.78 ^{a, c}	50.00 ± 4.40 ^{a, c}	64.00 ± 6.38	48.67 ± 6.75
3,000 lx	51.50 ± 5.63 ^{b, d}	54.42 ± 5.16 ^{b, d, e}	56.58 ± 7.03	58.42 ± 5.99 ^a

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 5-2 VAS of the Middle-aged group under six illuminance levels

100 lx and 3,000 lx. The VAS for Paper showed significant differences ($p < 0.05$) between 10 lx and 3,000 lx. In comparison, the subjects evaluated Paper as better than the other devices in the 3,000 lx illuminance condition.

Table 3-3 and **Figure 5-3** show a comparison of the senior middle-aged group's VAS for each illuminance. No significant differences were observed among the illuminance levels with the PW and iPad. The VAS for the SR showed significant differences ($p < 0.05$) between 10 lx and more than 300 lx, between 30 lx and more than 1,000 lx, and between 100 lx and 3,000 lx. The VAS for Paper showed significant differences ($p < 0.05$) between 10 lx and more than 100 lx, and between 30 lx and more than 300 lx, and between 100 lx and more than 1,000 lx. In comparison, the subjects evaluated Paper higher than the PW and iPad under the illuminance conditions higher than 1,000 lx, and higher than the SR at all illuminance levels. The slopes of the line graph in Figure 5-3 for the SR and Paper show similar movements and were affected more than the PW and iPad by the illuminance levels.

Table 3-3 Subjects' evaluation in the Senior middle-aged group using four devices under six ambient illuminance levels.

Ambient illuminance	1_PW (Mean±S.E.)	2_SR (Mean±S.E.)	3_iPad (Mean±S.E.)	4_Paper (Mean±S.E.)
10 lx	38.21 ± 5.12	14.19 ± 4.01 ^{a, b, c}	49.48 ± 5.05	19.57 ± 4.02 ^{a, b, c, d}
30 lx	41.08 ± 4.65	24.95 ± 3.81 ^{d, e}	53.24 ± 4.82	29.39 ± 4.46 ^{e, f, g}
100 lx	47.84 ± 4.08	31.04 ± 3.62 ^f	54.04 ± 3.69	39.44 ± 4.23 ^{a, h, i}
300 lx	51.44 ± 4.04	40.72 ± 4.10 ^a	54.48 ± 3.87	49.76 ± 3.22 ^{b, e}
1,000 lx	51.32 ± 3.82	49.08 ± 4.21 ^{b, d}	52.84 ± 3.92	58.28 ± 3.21 ^{c, f, h}
3,000 lx	51.00 ± 4.71	54.96 ± 4.86 ^{c, e, f, i}	52.08 ± 5.01	59.08 ± 4.00 ^{d, g, i}

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 5-3 VAS of the Senior middle-aged group under six illuminance levels

Table 3-4 Subjects' evaluations in the Elderly group using four devices under six ambient illuminance levels.

Ambient illuminance	1_PW (Mean $\pm$ S.E.)	2_SR (Mean $\pm$ S.E.)	3_iPad (Mean $\pm$ S.E.)	4_Paper (Mean $\pm$ S.E.)
10 lx	21.50 $\pm$ 4.45 a, b	5.40 $\pm$ 1.54 a, b, c	37.89 $\pm$ 5.94	10.33 $\pm$ 2.35 a, b, c
30 lx	34.00 $\pm$ 5.71	14.44 $\pm$ 3.04 ^{d, e, f}	41.22 $\pm$ 6.08	22.11 $\pm$ 3.26 d, e, f
100 lx	37.67 $\pm$ 6.12	23.56 $\pm$ 3.75 g, h	45.33 $\pm$ 7.18	32.78 $\pm$ 5.38 g, h
300 lx	41.11 $\pm$ 5.01	31.78 $\pm$ 3.92 ^{a, d, i}	53.56 $\pm$ 6.89	50.67 $\pm$ 5.31 a, d
1,000 lx	50.89 $\pm$ 5.64 a	49.00 $\pm$ 3.39 ^{b, e, g, i}	55.00 $\pm$ 8.26	59.78 $\pm$ 4.22 ^{b, e, g}
3,000 lx	50.11 $\pm$ 5.16 b	53.78 $\pm$ 2.50 ^{c, f, h, j}	52.22 $\pm$ 7.10	58.67 $\pm$ 5.26 c, f, h

†Values in the same column with the same letters are significantly different ($p < 0.05$) using ANOVA & the Scheffé multiple comparison procedure

Fig. 5-4 VAS of the Elderly group under six illuminance levels

Table 3-4 and **Figure 5-4** show a comparison of the elderly group's VAS for each illuminance. There was no significant difference among illuminance levels for the iPad. The VAS for the PW showed significant differences ($p < 0.05$) between 10 lx and more than 1,000 lx. The VAS for the SR showed significant differences ($p < 0.05$) between 10 lx and more than 300 lx, between 30 lx and more than 300 lx, between 100 lx and more than 1,000 lx, and between 300 lx and more than 1,000 lx. The VAS for Paper showed significant differences ($p < 0.05$) between 10 lx and more than 300 lx, between 30 lx and more than 300 lx, and between 100 lx and more than 1,000 lx. In comparison, the subjects rated Paper higher than the PW under illuminance conditions higher than 300 lx, higher than the iPad under illuminance conditions higher than 1,000 lx, and higher than the SR at all levels. The slopes of the line graph in **Figure 5-4** for the SR and Paper show similar movements and were affected more than the PW and iPad by the illuminance levels.

3.4 Evaluations by devices

Figures 6-1, 6-2, 6-3 and **6-4** show comparisons of subjects' device-specific evaluations (VAS) for each level of illuminance. We used the same data from figures 5-1,

Fig. 6-1 VAS in the Young group under six illuminance levels (*: $p < 0.05$) **Fig. 6-2** VAS in the Middle-aged group under six illuminance levels (*: $p < 0.05$) **Fig. 6-3** VAS in the Senior middle-aged group under six illuminance levels (*: $p < 0.05$)

5-2, 5-3 and 5-4 to evaluate the differences among devices. The mean scores for the iPad showed the best rating under illuminance conditions lower than 300 lx for all ages. There was no significant difference in the ratings for all devices under illuminance conditions

Fig. 6-4 VAS in the Elderly group under six illuminance levels
(*: $p < 0.05$)

higher than 300 lx with the exception of a difference between the evaluation of the iPad and SR by the middle-aged group. The mean scores for the SR without a front light were better than the scores for the PW with a front light for 3,000 lx in all ages.

4. Discussion

In this study, we used three indexes (VAS, reading time index, and correct answer rate index) to evaluate the readability of several devices. The illuminance level and type of device affected the VAS and reading time index; however, they had a low impact on the correct answer rate index. We confirmed that when the subjects rated readability as poor, they tended to read slowly and more accurately. In our previous studies, we found that there was an upper limit to the number of words that subjects could read aloud under illuminance of 300 lx with e-papers^{2) 8)}. This study showed that subjective performances declined with decreasing illuminance and that there was almost no significant difference in the subjective evaluations under illuminance conditions of higher than 300 lx with all devices. On the basis of prior studies (Lee et al.⁹⁾ and Kojima et al.¹⁰⁾) and this study, we suggest that illuminance of 300 lx is the limiting lighting level at which subjects can maintain their performance. The ISO¹¹⁾ recommends a level of 500 lx for indoor reading; therefore, we consider the ISO recommendation to be reasonable and proper. In a previous study⁸⁾, we showed the possibility of establishing a baseline score of 45 for VAS to indicate whether subjects have reached a sufficient level of reading of a text. In this study, the mean score for the VAS among all ages under illuminance conditions of 300 lx was 47.043 ± 1.30 (Young group: 46.125 ± 2.62 , Middle-aged group: 45.75 ± 3.18 , Senior middle-aged

group: 49.1 ± 1.98 , Elderly group: 44.278 ± 3.05). Taken together, our studies indicate that it is possible to set a baseline showing that subjects reach a sufficient readability level at a score of between 45 and 47.

With regard to the evaluations by age groups, the ambient illuminance had a greater impact on older age groups than the younger age groups with devices without lighting systems in the lower illuminance conditions. The elderly group's evaluations for all devices decreased substantially in the lower levels of illuminance, while the younger group found less difficulty in reading under these conditions. This difference could be related to cloudiness in the eye lens of many elderly subjects¹²⁾. In addition, we previously reported^{1) 2)} that the lighting systems of e-paper readers improved subjects' evaluation in the lower illuminance conditions. For these conditions, we suggested that the lighting systems of e-paper readers contributed to improving readability in older groups in the lower illuminance levels.

With regard to the evaluations by devices, as with our previous studies^{1) 2)}, in this study we found that the changes in the readability of reflective e-paper under various illuminance conditions were similar to those for paper text, and this tendency was remarkable in the older groups. The backlit LCD has its own light source and has a high resolution and contrast ratio, and no significant differences in reading were seen at any of the levels of illuminance. However, the evaluations for the backlit LCD were comparable in score to that for the paper text at 1,000 lx illuminance condition, while the best rating at 3,000 lx illuminance was obtained with the paper text. This result was similar to that of our previous study¹⁾. This study confirmed the superiority of built-in light systems under illuminance conditions of less than 1,000 lx compared to reflective devices, which was also similar to our previous study under illuminance conditions of less than 750 lx²⁾. As the subjects' evaluation for self-luminescent devices, especially by younger groups, tended to decrease with illuminance of 3,000 lx, improvement of readability under higher outdoor lighting levels remains as an issue to be solved.

5. Conclusion

This study investigated the effects of ambient illuminance and aging on the readability of e-papers. We summarize the findings as follows:

- (1) Illuminance of 300 lx was the limiting lighting level at which subjects could maintain their

performance.

- (2) The various ambient illuminance levels affected the readability among all ages, and had a greater impact on the older age groups than the younger age groups.
- (3) The lighting systems of e-paper readers contributed to improving readability for the older group in the lower illuminance conditions.
- (4) As the readability of self-luminescent devices tended to decrease with illuminance of 3,000 lx, these devices should perhaps not be recommended for use under higher outdoor lighting levels.

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