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Comparing reading processes on e-ink displays and print

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ABSTRACT

E-book reading devices open new possibilities in the field of reading. More activities than just reading a book can be performed with a single electronic device. For a long time, electronic reading devices have not been favored because their active LCD displays used to have a relatively low contrast. The new generation of electronic reading devices differs from earlier ones in the nature of the display: active LCD displays have been replaced with displays based on e-ink technology, which has display properties closer to that of printed paper. Moreover, e-ink technology has higher power efficiency, thereby increasing battery life and reducing weight. At first sight, the display looks similar to paper print, but the question remains whether the reading behavior also is equal to that of reading a printed book. In the present study, we analyzed and compared reading behavior on e-reader displays and on printed paper. The results suggest that the reading behavior on e-readers is indeed very similar to the reading behavior on print. Participants shared similar proportions of regressive saccades while reading on e-readers and print. Significant differences in fixation duration suggest that e-readers, in some situations, may even provide better legibility.

1. Introduction

An e-book, or "electronic book," is a digital format of a book. Electronic books open new possibilities in the field of reading. More functions than just displaying text can be integrated. For reading an e-book on a personal computer (PC), mobile phone, or personal digital assistant (PDA), a specialized software application for e-reading is necessary (e.g., Stanza). These reading devices have the disadvantage that the interface usually is an LCD display, which provides a relatively low contrast, especially in daylight conditions. Previous research showed that CRT and LCD displays are associated with impaired reading performance [1–3]. For instance, Mayes et al. [4] showed in their study that participants needed more time to read a text on a LCD screen than on a print. Cushman [5] reported that visual fatigue is significantly higher when reading black objects on a white screen than when reading on paper. Consequently, reading from LCD tends to be slower than reading from paper. Gould et al. [6] attempted to specify the causes of slowed reading on screens by analyzing eye movements. Results revealed that when reading from screens, participants made significantly more fixations per line, which, as a consequence, reduced reading speed. On average, they made 15% more forward fixations, while other eye movement parameters (like regressive saccades or re-fixations) for screen reading were comparable to those of reading on print. The authors explained the higher number of fixations in terms of image quality variables. Recent studies [7] suggest that such differences between print and screen have decreased but emphasize that reading behavior also depends on moderating variables like computer experience or the task to be performed. Nevertheless, there is still evidence of a preference for reading from print compared to doing so on LCD screens [8].

In addition to e-reading software for general electronic devices, there exist dedicated e-reading devices. These devices are commonly called e-book readers (or e-readers) and are purpose-built for reading. The first e-reading devices were prototyped in the late 1960s by Alan Kay, and they were later embodied in several product generations (Apple Newton, Palm Pilot) [9]. These series had built-in active LCD displays. Around the year 2000, several companies (e.g., Franklin, Hanlin, Hiebook, Rocket eBook) released new specialized e-reading devices. The latest generation of e-readers includes the Sony Reader, the Amazon Kindle, and the iRex iLiad. This generation of e-readers contains a different display technology: the active LCD displays have been replaced with "e-ink" technology [10]. The basic elements of e-ink are tiny microcapsules, with a diameter comparable to that of a human hair. Each microcapsule contains positively charged white particles and negatively charged black particles suspended in a clear fluid. When an electric field is applied, the white particles move to the top of the microcapsule where they become visible to the user. This makes the surface appear white at that spot. At the same time, the black particles move to the bottom of the microcapsules, where they are not visible. By reversing the electric field, the black particles appear at the top of the capsule, which now makes the surface appear dark at that spot [11]. Since only

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Table 1
Device specifications.[a]

Reading device	Font size in mm	Font size in degree (visual angle)	Monitor size	Device size	Weight	Resolution
iRex	3–4	0.286– 0.382	162 × 122 mm	215 × 154 × 14 mm	400 g	160 dpi
Bookeen	2–7	0.191–0.668	122 × 92 mm	188 × 118 × 8.5 mm	174 g	166 dpi
BeBook	3–4	0.286–0.382	90 × 120 mm	184 × 120.5 × 9.9 mm	230 g	166 dpi
Sony	2–6	0.191–0.573	90.6 × 122.4 mm	175 × 122 × 8 mm	260 g	170 dpi
ECTACO jetBook	1–4	0.095–0.382	105 × 80 mm	153 × 109 × 10 mm	215 g	160 dpi
Classic paper book	3	0.286	164 × 94 mm	206 × 125 × 44 mm	650 g	–

[a] Participants were able to choose the font size along with e-reading devices; specifications show the range of font sizes.

refreshing the display but not maintaining it requires energy, e-ink technology has the advantage of low power consumption, thereby allowing for increased battery life or reduced weight [9].

However, there are many other factors that set the reading experience on e-readers apart from that on printed-paper books or on screens. The size of the device, the scalable font size, and the new e-ink technology make it different from reading from printed paper or from screen. It seems that the advancements in screen quality with the e-ink technology have made reading from these devices increasingly acceptable. Additionally, the advantages in terms of low weight, small dimensions, and freedom of mobility are evident. Previous studies have shown that reading on an e-reader without e-ink display causes significantly higher visual fatigue than reading on print [12]. An assessment of the readability of e-readers with e-ink displays showed no difference in reading speed between the Kindle2 and a printed book [13]. This result suggests that e-ink technology allows for a reading process that is similar to that of reading print. However, there is no empirical evidence that the new e-ink technology is beneficial with regard to the reading process.

The objective of the present study is to evaluate and compare human reading behavior on e-ink and print as measured by eye tracking. If reading on e-ink displays is similar to reading print, then no differences in eye movement patterns (e.g., progressive- and regressive saccades and fixations) and in reading performance (e.g., reading speed) should be found.

2. Material and methods

2.1. Participants

Ten participants (five females, one left handed) were tested. The mean age was 42 years, with a range from 16 to 71 years. The participants were selected such that a wide range of possible e-reader users was covered. Properties like subjective media experience, education, and subjective reading-skills were balanced in the selection of participants. All participants reported normal or corrected to normal vision. None of the participants had previous experience with e-readers. Participants gave written informed consent before participation. The study was performed in accordance with the latest declaration of Helsinki.

2.2. Apparatus

Eye movements were recorded with an infrared-video eye-tracking device (X120 Eye Tracker, Tobii Technology, Danderyd, Sweden). The system has a sampling rate of 120 Hz and spatial tracking accuracy of approximately 0.5° of visual angle (largely depending on calibration quality). Because of the system requirements of the eye-tracking setup, the participants were seated on a chair at a fixed distance of approximately 60 cm from the eye tracker and stimulus. To make sure that participants were able to read at this fixed distance, they were allowed to individually adjust the font size. Movements of the head were allowed within a virtual box of approximately 30 × 20 × 30 cm.

2.3. Stimuli

To get a representative overview and to compare different e-readers, five e-readers and one printed paper book were chosen for this study. The criterion for the selection of the e-readers was their commercial availability in Switzerland. The five e-readers were (a) iRex iLiad,[1] (b) Sony PRS-505,[2] (c) BeBook,[3] (d) ECTACO jetBook,[4] and (e) Bookeen Cybook, Gen 3.[5] Table 1 shows technical specifications of the six reading devices. Fig. 1 illustrates the e-readers and the printed paper used in this study. Text material was a novel [14] in German language, which was the native language of all participants. Every participant read the first 12 pages from the novel as part of a legibility-test (one page on each reading device in two test sessions). The number of words read on each device, including printed paper were equal (300 words per section).

2.4. Experimental procedure

First, the participants were given the instructions about the experiment, which consisted of three parts: A legibility test with eye tracking was performed at the beginning and at the end. Between the two legibility tests, the participants had to fill out questionnaires, execute tasks, and had a short resting period of 15 min. The first legibility test started with the calibration of the eye tracker. Calibration was repeated for every device to ensure the best possible tracking quality. Participants were required to silently read one page on each reading device. Pages 1–6 of the novel were read on five e-Readers and one classic paper book (one page per device) while their eye movements were recorded. After the first legibility test, the participants were interviewed, and they were asked to assign marks and subjective preferences to each reading device. Then, the subjects were given two hours to use each reading device and execute specific tasks on the devices, like opening a specified text at a requested page [15]. After this testing phase, the second legibility test was performed, which was identical to the first legibility test with the exception of different text segments (pages 7–12). After the second legibility test, the participants were interviewed again and asked to give their overall subjective judgments. The design of the experiment was within subject, i.e., each participant was tested with each device, therefore reducing the effects of individual differences. The sequence of the reading devices presentation (including printed paper) was randomized to control for order effects.

3. Data analysis

Previous research has shown that legibility influences reading [16–20]. If the letters in text are more difficult to decode, reading typically slows down as readers make more and longer fixations [21–24]. Therefore, oculomotor behavior represents an objective

[1] iRex Technologies (NL).
[2] Sony Electronics (USA).
[3] Endless Ideas BV (NL).
[4] ECTACO (DE).
[5] Bookeen (FR).

Fig. 1. The six reading devices used in this study. Classic paper book, Bookeen Cybook Gen, BeBook, Sony PRS-505, ECTACO jetBook, iRex iLiad (from upper left to lower right).

measure to compare the legibility of e-readers and printed paper [23,24]. The next two sections give an overview of the relevant parameters in measuring oculomotor reading behavior.

3.1. Fixations

When reading, the subjective feeling of the reader is that the gaze moves continuously over the text. However, in reality, the eyes do not move at a constant speed; they make a series of approximately 3–4 jumps per second (called saccades, see below) with short stops in between (called fixations). Fixations allow the visual system to pick up information by aligning the fovea with an element of interest. The fovea is a small area in the middle of the retina, which is densely packed with visual receptors (cones), which enable sharp vision. Typically, fixation duration varies between 150 and 500 ms. In the context of readability, two factors are important: content or text difficulty and the physical characteristics of the text. On one hand, text difficulty has an influence on fixation durations and the number of fixations [25]. On the other hand, physical characteristics like contrast or font characteristics have an influence on the fixation durations and the number of fixations [22–24]. Fixation duration is a well-established indicator of the difficulty of perceptual and/or cognitive processing in reading [21,26].

3.2. Saccades/regressions

Between fixations, there are quick jerks, called saccades. In reading, three types of saccades are important: rightward "progressive" saccades in the direction of the text, leftward "regressive" saccades (regressions) opposite to the direction of the text, and line return sweeps connecting the end of a line with the beginning of the next. Regressive saccades are backward moves within a line, which serve to re-examine material not clearly perceived or understood [18]. Regressive saccades represent roughly 14% of all saccades in adults and about 25% of all saccades in children [27]. The proportion of regressive saccades depends on the text difficulty (the more difficult the text material, the more the regressive saccades), on the reader's reading skills, (the worse the reading skills, the more the regressions), and on the physical characteristics of the text [21,28]. An increase in regressive saccades is an indicator of reduced legibility [19,29].

In the present study, we analyzed the two oculomotor parameters described above: fixations (number and duration) and saccades (progressive, regressive, and line sweeps). Saccades were computed based on the positional information of consecutive fixations; A saccade is defined as the direction and distance between two consecutive fixations. Two types of saccades were distinguished: rightward "progressive" saccades (positive *x*-vector) and leftward "regressive" saccades (negative *x*-vector). Leftward saccades exceeding more than 70% of line length were classified as line sweeps. Large saccades exceeding the dimensions of the reading device were considered as artefacts and excluded from the analysis; resulting in excluding 2% of saccades.

3.3. Reading performance

Reading time was calculated on the basis of time codes from the eye movement recordings. The time stamps for starting/stopping reading and page-turns were coded offline for later statistical analysis. Statistical analysis was performed using F-statistics based on a repeated measures ANOVA with the within factor book (iRex, Bookeen, BeBook, Sony, ECTACO, classic paper book). Post-hoc tests were calculated using *t*-tests. In cases of unequal variances, Friedman-tests (using χ^2 statistics) were employed (post hoc tests were calculated using Wilcoxon tests). Reading speed was measured in words per minute.

Table 2
Mean fixation duration.[a]

Reading device	Mean fixation duration (ms)	SD	Significant difference to (post-hoc)
iRex	278.5	34.9	BeBook, Sony
Bookeen	292.6	51.4	BeBook, Sony
BeBook	326.2	62.7	iRex, BeBook
Sony	316.2	43.1	iRex, Bookeen
ECTACO jetBook	349.5	116.9	–
Classic paper book	422.2	256.7	–

[a] The mean fixation duration differed significantly between the devices [Friedman $\chi^2(5) = 25.063$, $p < 0.001$].

Table 3
Number of fixations.[a]

Reading device	Numbers of fixations	SD	Significant difference to (post-hoc)
iRex	302.4	75.8	–
Bookeen	327.3	69.5	ECTATO, paper
BeBook	325.1	81.8	Paper
Sony	321.0	82.7	Paper
ECTACO jetBook	284.7	87.9	Paper, Bookeen
Classic paper book	266.2	78.2	Bookeen, BeBook, Sony

[a] The number of fixations differed significantly between the books [$F(5, 40) = 3.609$, $p < 0.01$].

Table 4
Number of letters per fixation.[a]

Reading device	Numbers of letters per fixation	SD	Significant difference to (post-hoc)
iRex	5.9	1.5	Paper
Bookeen	5.4	1.2	Paper
BeBook	5.8	2.4	Paper
Sony	5.7	1.8	Paper
ECTACO jetBook	6.5	2.3	–
Classic paper book	7.1	3.0	iRex, Bookeen, BeBook, Sony

[a] The numbers of letters per fixations differed significantly between the books [Friedman $\chi^2(5) = 14.460$, $p < .05$].

3.4. Additional measures

We measured page-turns while reading. Page-turns are related with font-size and display size; participants were able to adjust font-size.

We measured the luminance (cd/m^2) of the font (I_F) and the background (I_B) using a luminance meter (Minolta LS-110). Based on these measurements, we computed the font–background contrast by means of Weber contrasts [$CW = (I_F - I_B)/I_B$] Measurements were taken under constant surround illumination. Because of the negative polarity (black font against white background), the contrast values are negative.

4. Results

4.1. Eye movement behavior: Fixations

4.1.1. Mean fixation duration

Table 2 shows mean fixation duration for each device. The mean fixation duration differed significantly between different reading devices [Friedman $\chi^2(5) = 25.063$, $p < 0.001$]. Participants made the shortest fixations, i.e., were most efficient in extracting information from the display, when reading on the iRex e-reader (278.5 ms) (see Table 2).

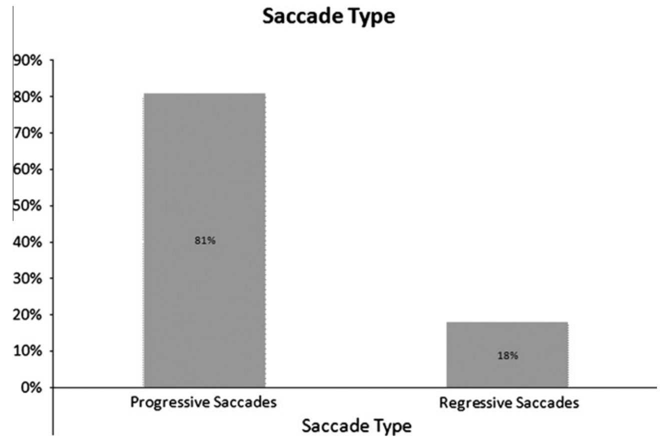

Fig. 2. Proportion of saccade types.

4.1.2. Number of fixations

The number of fixations differed significantly between the books. On paper book the lowest number of fixations was needed for reading the text [$F(5, 40) = 3.609$, $p < 0.01$] (see Table 3).

4.1.3. Number of letters per fixation

The mean number of letters, which were read per fixation (i.e., the ratio of total number of letters divided by the number of fixations), was significantly affected by the type of book [Friedman $\chi^2(5) = 14.460$, $p < 0.05$]. On printed paper, the largest number of letters was covered on average in one fixation (see Table 4).

4.2. Eye movement behavior: Saccades

Saccades were computed based on the positional information of consecutive fixations, saccades (the direction and distance between two consecutive fixations).

Of the remaining saccades 81% were progressive (Mean number (progressive) = 213.1, SD = 15.6) and 18% were regressive (Mean number (regressive) = 46.8, SD = 4.1). The mean number of line return sweeps was 39.4 (SD = 7.9) (see Fig. 2).

4.2.1. Percentage of regressive saccades

No significant differences in the percentage of regressive saccades (percentage regressive/regressive + progressive)[6] were found between the different reading devices [$F(5, 40) = 0.298$, $p = 0.911$].

4.3. Reading performance

4.3.1. Reading speed

Reading speed was measured in words per minute.

No significant effect on reading speed [$F(5, 40) = 1.113$, $p = 0.369$] was found. The number of words read per minute did not differ between the different books (range 188–220 words per minute) (see Table 5).

4.4. Page-turns

The number of page turns was significantly different between the reading devices [$F(5, 40) = 22.729$, $p < 0.001$] (see Table 6).

[6] Line return sweeps were excluded.

Table 5
Number of words per minute.

Reading device	Mean number of words per minute	SD
iRex	220	83.4
Bookeen	192.1	59.3
BeBook	191.1	61.4
Sony	201.2	78
ECTACO jetBook	201.7	69.6
Classic paper book	187.8	60.6

Table 6
Number of page-turns.[a]

Reading device	Mean number of page-turns	SD	Significant difference to (post-hoc)
iRex	1.6	0.4	Bookeen, ECTACO, paper
Bookeen	3.5	1.3	iRex, BeBook, Sony, ECTACO, paper
BeBook	1.8	0.6	Bookeen, ECTACO, paper
Sony	2.1	0.4	Bookeen, ECTACCO, paper
ECTACO jetBook	2.8	0.9	iRex, Bookeen, BeBook, Sony, paper
Classic paper book	0.7	0.4	iRex, Bookeen, BeBook, Sony, ECTATO

[a] The number of page-turns was significantly different between the reading devices [$F(5, 40) = 22.729$, $p < 0.001$].

Table 7
Weber contrasts.[a]

Reading device	Font luminance I_F	Background luminance I_B	Weber contrast $C_W = (I_F - I_B)/I_B$
iRex	3.17	17.8	−0.82
Bookeen	3.91	17.7	−0.78
BeBook	3.52	17.8	−0.80
Sony	4.10	17.9	−0.77
ECTACO	2.10	13.4	−0.84
Printed paper	2.91	30.6	−0.90

[a] Weber-contrasts (C_W) of black font (I_F) on white background (I_B). (I – Luminance in cd/m^2).

4.5. Luminance and contrast

We measured the luminance (cd/m^2) of the font (I_F) and the background (I_B) using a luminance meter. Printed paper has the best contrast, but the contrasts of the e-reader displays are comparable to that of paper (see Table 7).

4.6. Subjective preferences

Participants were asked to rate subjective preferences for reading on each device. Subjective readability was judged on a Likert-scale from 1 (very bad) to 6 (very good). We found significant differences in subjective readability in the first and the second reading sessions ($x^2(5) = 20.542$; $x^2(5) = 20.286$). Table 8 shows the mean of the subjective readability ratings.

5. Discussion

Overall, the results suggest that the legibility of the current e-reader generation is fairly good. The reading behavior for e-ink displays, measured in eye movements, is very similar to the reading behavior for classic paper books. The mean percentage of regressive saccades (18%) is rather high. According to Findlay [17], 18% regressive saccades are normal when reading a scientific text. In fact, our text was not even scientific; thus, the rather high rate of regressive saccades could be explained by the laboratory setting and the relatively large reading distance or by the effort of participants to perform as well as possible in the experiment. The finding that the regressive saccades for the e-reader and printed paper is similar confirms the main result that participants did not have greater difficulty with reading on e-readers compared to printed paper. However, we found significant differences in fixation durations. Fixation duration can be used as a measure of legibility. During fixations, when the eye stands still for a short period of time, visual information is extracted and cognitive processing is applied [25]. If a reader fixates a letter or a word for a longer duration, it can be taken as empirical evidence that the reader has problems in extracting visual and/or linguistic information. Since the same text was read, counterbalanced over readers and devices, we interpret longer fixations as being caused by lower legibility. Our results show that participants had significantly longer fixations when reading on a printed book compared with reading on e-reading devices.

The question that arises is in what respect e-readers show better legibility than printed paper. We must be aware of the fact that participants, when reading on the e-readers, had the possibility to choose the font size that was most comfortable for them. However, when reading on the printed paper, this setting was not available. Since viewing distance was relatively constant and font size of the printed-paper book was comparatively small, some participants (especially older participants) had difficulties with reading, resulting in longer fixations. It is well known that optimal font size is a factor of good legibility [18,19], and therefore, the possibility of choosing an optimal font size is related to improved legibility. Therefore, we can conclude that in some situations, e-readers have a better legibility than printed books. For example, it is conceivable that people with a visual impairment will have a definite advantage with the possibility to adjust font size. The fact that participants were free to adjust font size may also explain the differences in the total number of fixations, the number of letters per fixation, and the number of page turns.

In contrast to previous studies [1–5], which compared CRTs and LCDs with print, we found no significant differences in the reading speed. E-ink technology differs in many respects from LCD-displays: it has good visibility under a wide range of ambient light

Table 8
Subjective readability ratings rating (Likert-Scale 1 (very bad) to 6 (very good).[a]

Reading device	Mean readability ratings (test1)	SD	Significant difference to (post-hoc)	Mean readability ratings (test2)	SD	Significant difference to (post-hoc)
iRex	5.2	1.0	BeBook, ECTACO	5.3	0.82	BeBook
Bookeen	5.3	0.6	BeBook, ECTACO	4.7	0.86	ECTATO
BeBook	3.5	1.3	iRex, Bookeen, Sony, paper	4.25	1.0	iRex, paper
Sony	4.5	1.4	BeBook	4.85	1.25	ECTATO
ECTACO jetBook	4.2	1.2	iRex, Bookeen	3.8	1.40	iRex, Bookeen, Sony, paper
Classic paper book	5.2	1.0	BeBook	5.35	0.94	BeBook, ECTATO

[a] The subjective readability ratings differed significantly between the books [$x^2(5) = 20.542$; $x^2(5) = 20.286$].

conditions, including direct sunlight. The luminance measurements confirm that e-readers have a contrast similar to paper. The printed paper book still has the best contrast (CW = −90; black font size on white background), but the contrast of the e-reader display is still comparatively good (CW = −77 to −84). Subjective interview data confirmed that participants felt comfortable while reading on e-reading devices based on e-ink technology, but they had problems in handling some of the devices.

6. Conclusions

This study compared the reading processes in terms of eye movement behavior, while reading on e-ink displays and on printed paper. The results show that the reading behavior when reading on an e-reader is very similar to the reading behavior when reading on printed paper. In contrast to LCD-displays, which have been associated with impaired reading performance, e-ink displays are an important milestone in the field of reading.

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