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Reading on LCD vs e-Ink displays: effects on fatigue and visual strain

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Abstract

Purpose: Most recently light and mobile reading devices with high display resolutions have become popular and they may open new possibilities for reading applications in education, business and the private sector. The ability to adapt font size may also open new reading opportunities for people with impaired or low vision. Based on their display technology two major groups of reading devices can be distinguished. One type, predominantly found in dedicated e-book readers, uses electronic paper also known as e-Ink. Other devices, mostly multifunction tablet-PCs, are equipped with backlit LCD displays. While it has long been accepted that reading on electronic displays is slow and associated with visual fatigue, this new generation is explicitly promoted for reading. Since research has shown that, compared to reading on electronic displays, reading on paper is faster and requires fewer fixations per line, one would expect differential effects when comparing reading behaviour on e-Ink and LCD. In the present study we therefore compared experimentally how these two display types are suited for reading over an extended period of time.
Methods: Participants read for several hours on either e-Ink or LCD, and different measures of reading behaviour and visual strain were regularly recorded. These dependent measures included subjective (visual) fatigue, a letter search task, reading speed, oculomotor behaviour and the pupillary light reflex.
Results: Results suggested that reading on the two display types is very similar in terms of both subjective and objective measures.
Conclusions: It is not the technology itself, but rather the image quality that seems crucial for reading. Compared to the visual display units used in the previous few decades, these more recent electronic displays allow for good and comfortable reading, even for extended periods of time.

Introduction

In recent years there has been strong competition among manufacturers and publishers to produce and distribute state-of-the-art reading devices that are light, mobile, have high display resolutions and come with various other features. One major distinction between different types of electronic reading devices is the display technology used. There are currently two prominent display types: LCD and e-Ink displays.[1] LCD displays are multipurpose and used in tablet computers such as the Apple iPad or so called ‘smart’ phones. They are usually backlit and can be used in the dark. E-Ink displays were engineered to be as close to paper as possible and like classic paper external light is needed to read on them. E-Ink is used in dedicated eBook reading devices like the Kindle, Sony e-reader and others. There is a lot of discussion about which type of display is better for reading, especially since e-Ink devices do not need to refresh the screen for static media presentation. Therefore it could be assumed that reading on e-Ink devices is better compared to LCD-screens with respect to possible negative health effects, as found in earlier studies on continuous screen handling. While many personal and anecdotal reports can be found on the internet, empirical evidence is sparse. Therefore it is important to do research in this area to see whether the new technology causes more visual fatigue or not.

Most of the research on reading continuous text from Visual Display Units (VDU) was undertaken at the beginning of the internet boom until the early 1990s and repeatedly reported that compared to reading from paper, reading from VDU is slower, less accurate, more fatiguing and less liked by readers.[2–8] However since then display technology has evolved, CRT-screens are no longer available and in current technologies the quality of displayed text is much improved with respect to resolution, contrast, and flickering. Nonetheless it is still a matter of debate as to whether reading is better in paper, e-Ink or LCD. The present study was aimed at comparing extended reading on e-Ink and LCD regarding their possible effects on (visual) fatigue and eye movements. To this end participants read for a total of 3 h while, at regular intervals, subjective (fatigue) and objective (eye movements) effects were assessed.

According to the 10th revision of the International Classification of Diseases (ICD-10) of the World Health Organization (WHO) visual fatigue, also termed visual strain, is classified as a subjective visual disturbance (H53.1) and characterized by fatigue, pain around the eyes, blurred vision or headache. In the present study these subjective aspects were assessed using subjective ratings and a paper-pencil attention test. Reading itself on the other hand is characterised by specific eye movements[9]: fixations, during which perception occurs, and saccades moving to the locus of the next fixation. These saccades normally have a rightwards reading direction. Saccades against the reading direction, so called regressive saccades, result in refixations of specific text locations and indicate difficulties in text perception or comprehension. To test whether extended reading on different devices affects oculomotor behaviour, eye movements were recorded as an objective measure: research in this field revealed changes in eye-movement behaviour related to the experienced level of fatigue.[10] We hypothesised that the greater the fatigue, the higher the number of regressive saccades. To further assess possible fatigue experienced by the participants, we additionally conducted a concentration test, since other studies have found that the state of fatigue often coincides with a reduced ability to concentrate.[11] Additional to the above mentioned measures, the pupillary light reflex was analysed as an additional objective measure to detect possible fatigue effects on the visual system. This reaction of the pupil to a flash of light has been discussed as a possible measure of fatigue,[12,13] but see[14] for a critical discussion. Our hypothesis was that greater visual fatigue would be found when reading with the LCD device than when reading with the e-Ink device.

Methods

Participants

Ten participants (5 female, all right handed) volunteered to take part in the experiment. Their mean age was 37.4 years (SD 12.02, range 20–57). All had normal or corrected to normal vision (0.0 logMAR or better, equivalent to 6/6 or 20/20 Snellen or better), no strabismus and reported not having any eye disease. The study was performed in accordance with the latest declaration of Helsinki and all participants gave written informed consent prior to participation.

Apparatus

The experiment took place in a room with constant artificial light conditions (indirect ceiling light) without direct sunlight. The reading devices (see *Figure 1*) used were one e-reader with e-Ink (Sony e-reader Model PRS-600; http://www.sony.co.uk) and a Tablet with backlit LED-Screen (Apple iPad, first generation; http://www.apple.com). For both devices the luminance (cd m^{-2}) of dark font and light background was measured using a luminance meter (Minolta LS-110, http://www.konicaminolta.com). Specifications of the reading devices are shown in *Table 1*. In the test blocks, eye movements were recorded using an infrared-video remote eye-tracker (Model X120, Tobii Technology, Danderyd, Sweden; http://www.tobii.com) with a sampling rate of 120 Hz and a spatial tracking accuracy of approximately 0.5° of visual angle largely depending on calibration quality. For eye movement recording participants were seated on a chair at a fixed distance from the eye-tracker which was positioned below a 22″ LCD Computer screen (HP LP2275w; http://www.hp.com) which was used to display the stimuli for measuring reading saccades and the pupillary light reflex.

Stimuli and procedure

The experiment took place in two sessions separated by at least 1 week. The experimental procedure of such a session is illustrated in *Figure 2*. All sessions started in the morning at 8:30am and consisted of four blocks, each of which included a test block and a reading block (see below).

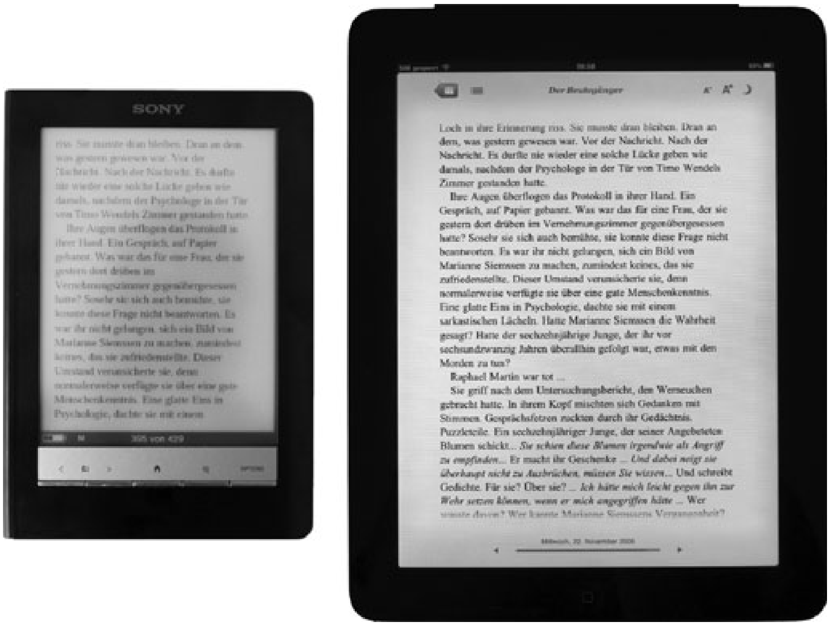

Figure 1. The two eReading devices used in the experiment. Left: Sony PRS 600. Right: Apple iPad (first generation). Please note that the display contrast as seen on the photograph is not as perceived in real conditions.

Table 1. Display specifications of the two eBook reading devices compared: The Sony eReader Model PRS-600 with e-Ink and Apple iPad (first generation) with backlit LED. Luminance was measured under the same lighting conditions that were present during the experiment

Device	LCD	e-Ink
Device dimensions	24.3 × 19 cm	17.5 × 12.2 cm
Display size	9.7″	7″
Display resolution	1024 × 768 pixels	800 × 600 pixels
Luminance light (I_B)	155.3 cd m^{-2}	141.0 cd m^{-2}
Luminance dark (I_F)	60.8 cd m^{-2}	60.8 cd m^{-2}
Weber contrast, $(I_F–I_B)/I_B$	−0.61	−0.57
Refresh rate	60 Hz	none (static display)

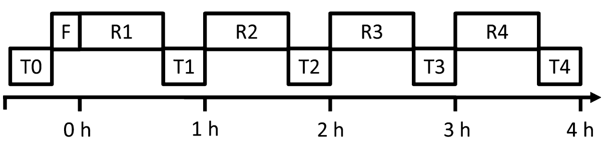

Figure 2. Schematic diagram of the experimental procedure used in the test sessions. T 1–5 represent test blocks, R 1–5 represent reading blocks and *F* represents the initial familiarization phase.

Reading block.

In each session the participants' task was to read for an extended period of time (4 × 45 min) on either an e-Ink or LCD device. The order of reading devices was counterbalanced across participants with half of the participants reading from the e-Ink and half of the participants reading from the LCD display first. The reading material consisted of a German novel[15] presented in dark characters on light background. Due to changes in reading position, reading distance varied from approximately 30 to 40 cm and perceived font size varied between 0.43 and 0.57° vertical visual angle. Each reading block consisted of continuous reading for 45 min. A deck chair and a wicker chair were provided to allow the subject to adopt a comfortable position. During the reading block participants were allowed to take mineral water and pretzels, which were provided. Other comestibles were not allowed in order to minimise possible fluctuations in fatigue levels e.g., due to blood sugar levels or caffeine.

At the beginning of the first reading block the participants were given 10 min to familiarize themselves with the respective device. This was to avoid possible effects simply due to novelty or handling problems with the reading device. Then the experimenter adjusted font size if desired, and explained how to turn the pages. After the participant had had an opportunity to ask questions, they started reading and continued to do so for 45 min. In the following blocks (block two, three and four) the participants continued reading without repetition of the initial familiarisation phase. In each block the number of pages read was recorded by the experimenter.

Test block.

The reading blocks were followed by a test block which included questions assessing general fatigue and visual-strain, a visual attention test (letter cancellation) a reading test and a measurement of the pupillary light reflex. The next reading block started immediately after the test block.

Questionnaire: General fatigue was assessed with a single question which had to be answered on a scale from 1 (very tired) to 7 (fully awake). Visual strain was assessed with six questions taken from Heuer, Hollendiek, Kröger & Römer[16] comprising declarations such as 'my eyes feel tired' 'I have difficulties in seeing', and 'I have a headache' and had to be answered on a 7-point Likert scale from 1 (not at all) to 7 (very much). The mean of the responses to these six items was taken as a measure of visual fatigue. Responses to the general fatigue questionnaire were analysed as given. The responses of the six questions assessing visual strain were averaged for each participant and time.

Visual Search Task: To test for any possible effects of reading strain on visual attention we constructed a cancellation test in five parallel versions. An example is illustrated in *Figure 3*. It consisted of eight lines of mixed upper case letters with a total of ten identical target letters in each version. Participants had to search for a specific target letter line by line as fast as possible and cancel all of them. Participants did not know how many times the specified letter appeared in the matrix. The time needed and the number of omissions was counted. For the cancellation test the mean time needed for each target was computed by dividing the total time needed to perform the task by the number of targets found. This would account for possible speed-accuracy tradeoffs.

Reading Task: The reading task consisted of reading one page (approximately 280 words) on a TFT computer screen while eye movements were recorded. The font size of the presented text material was 5×5 mm for capital letters. After each reading test two questions about the content of the text were asked to see whether the participants had processed the text material or not. From the recorded eye movements of the reading task mean fixation duration was taken as a global variable. Additionally each fixation was classified either as progressive, regressive or line sweep, depending on its relative position to the previous and subsequent fixation. Leftward fixations 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.

Pupillary Light Reflex: For the measurement of the pupillary light reflex the participants looked at the centre of a black TFT computer screen for 5 s. Three white flashes (white screen) of 200 ms separated by 5 s (black screen) each caused a pupil contraction, which was recorded by the eyetracker. The latency of the pupillary light reflex was computed as the lag in milliseconds (ms) between flash onset and beginning of pupil contraction.

Analysis

Statistical analysis was performed using a 2×5-way repeated measures ANOVA with the within factors device (Tablet, e-Ink) and time (pretest [T0], Test 1 [T1], Test 2 [T2], Test 3 [T3], Test 4 [T4]). Data distribution was tested for normality (Kolmogorov–Smirnov test) and all data were normally distributed.

Results

Subjective fatigue/Questionnaires

Questionnaires.

General Fatigue: Data of general fatigue are shown in the left part of *Figure 4*. We performed a 2×5-factorial analysis of variance with the two factors device and time manipulated within subjects. The analysis yielded significant effects for time $F_{1,4} = 5.96$, $p = 0.001$ and

Q A Y F W S X D C E R V T F G B Z H N U
F J M I K O L P A W F S X D R C E T V G Z
B H U N F J I K O L P Q F W E R T Z U I O
F P A S D G E F H J K L E Y X C V B N M Q
W A S Y R D X T F C G E V U H B I F J N O
K Y E Q A X W S C D V R B T G N Z E H M
U J K I E O L P T K H B D T M Y N C L A K
G H D J K A S L O Q I T E U R P W L K U Z

Figure 3. Example of one of the five cancellation tests used. In this example the target appearing 10 times is the letter 'E'. Letter size was 6 mm, weber contrast ($(I_F - I_B)/I_B$) was –0.90, viewing distance was approximately 20–40 cm.

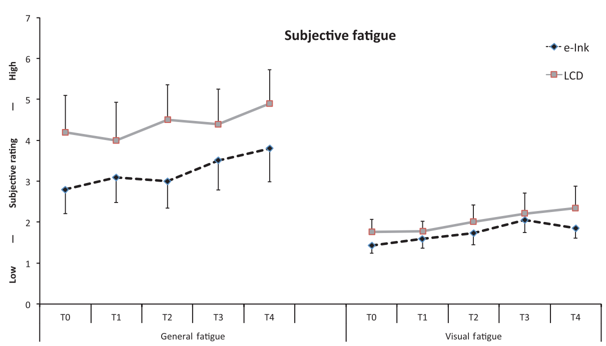

Figure 4. Mean general fatigue and visual fatigue as assessed by the questionnaire. Error bars indicate SEM.

device $F_{1,9} = 9.84$, $p = 0.01$. The interaction was not significant $F_{1,4} = 0.47$, $p = 0.76$. Subjective fatigue increased over time. This effect was independent of the reading device since the main effect of device on subjective fatigue was already present in the baseline measurement before reading and reflected a difference in the baseline condition.

Visual Fatigue: Data from the visual fatigue questionnaire are shown in the right part of *Figure 4*. We performed the same 2 × 5-factorial analysis of variance with the factors device and time manipulated within subjects. The analysis yielded no significant main effects ($p > 0.10$). Visual fatigue as assessed by the questionnaire neither changed over time nor did it differ between the two devices. Also the interaction was not significant $F_{1,4} = 0.33$, $p = 0.86$. The same 2 × 5- factorial analysis was performed for each question. No significant main effects were found ($p > 0.05$).

Visual search task

The results for the visual search task are shown in *Table 2*.

A 2 × 5-factorial analysis with the factors device and time manipulated within subjects revealed no significant main effects or interactions on the mean time required to perform the cancellation task ($F_{1,4} = 1.16$, $p = 0.19$), the number of targets found ($F_{1,4} = 0.84$, $p = 0.51$), or the mean time per target found ($F_{1,4} = 1.69$, $p = 0.17$). Performance on the cancellation task did not change within and between the test sessions.

Reading speed

To analyse possible differences in reading speed we performed a 2 × 4–factorial analysis of variance with the factors device (Tablet, e-Ink) and reading block (number of pages read within 45 min). One page was defined as a display on the reading device corresponding to approximately 280 words. To account for differences in the display size of the devices, pages were counted in words per minute. The results for reading speed are shown in *Table 3*.

There were no significant main effects of time ($F_{1,3} = 1.90$, $p = 0.15$) and device ($F_{1,9} = 0.12$, $p = 0.74$) or significant interactions ($F_{1,3} = 1.15$, $p = 0.35$). Reading speed in words per minute (i.e. the number of pages read in 45 min) remained constant over time and between the devices.

Oculomotor reading parameters

Mean fixation duration.

The mean fixation durations are shown in the upper part of *Table 4*. A 2 × 5–factorial analysis of variance with the within factors device ($F_{1,9} = 0.02$, $p = 0.90$) and time ($F_{1,4} = 0.99$, $p = 0.43$) revealed no significant effects on the mean fixation duration. Mean fixation duration did not change between the devices or over time.

Regressive fixations.

The percentage of regressive fixations are shown in the lower part of *Table 4*. The same 2 × 5–factorial analysis of variance revealed no significant main effects of time ($F_{1,4} = 1.30$, $p = 0.29$) or device ($F_{1,9} = 1.00$, $p = 0.34$) on the number of regressive fixations. The number of regressive fixations did not differ between the devices ($F_{1,9} = 0.49$, $p = 0.50$) or change over time ($F_{1,4} = 2.50$, $p = 0.06$). The device × time interaction reached significance $F_{4,9} = 2.74$, $p = 0.04$. This result was due to the relatively low proportion of regressive saccades measured in T1 and T4 after reading on e-Ink.

Pupillary light reflex

The pupillary light reflex was judged by an operator based on the graphical illustrated eye tracking data. *Figure 5* shows an example of a typical distribution and how the

Table 2. Time required to perform the visual search task, number of hits and the resulting mean time (in seconds) per hit for each device and measurement. Standard deviations in brackets

	T0	T1	T2	T3	T4
Mean total time (in s)					
e-Ink	27.05 (1.96)	28.70 (1.89)	30.47 (2.05)	28.84 (1.79)	28.52 (2.65)
LCD	26.69 (2.04)	30.17 (1.74)	28.68 (2.43)	29.73 (2.43)	30.20 (2.43)
Number of hits					
e-Ink	9.3 (0.52)	9.4 (0.27)	9.0 (0.39)	9.6 (0.22)	9.3 (0.21)
LCD	9.4 (0.22)	9.0 (0.39)	9.0 (0.37)	9.3 (0.34)	9.6 (0.16)
Mean time per hit					
e-Ink	2.94 (0.17)	3.08 (0.22)	3.40 (0.22)	3.00 (0.16)	3.06 (0.28)
LCD	2.84 (0.20)	3.41 (0.24)	3.23 (0.29)	3.22 (0.27)	3.15 (0.26)

Table 3. Reading speed in words per minute for each reading block (R1–R4) and device. Standard deviations in brackets

	R1	R2	R3	R4	Total mean
Mean words per minute					
e-Ink	319 (15)	291 (18)	305 (15)	323 (17)	309 (14)
LCD	302 (13)	292 (20)	325 (24)	300 (18)	305 (15)

operator decides. A 2×5–factorial analysis of variance with the within factors device ($F_{1,9} = 2.18$, $p = 0.17$) and time ($F_{1,4} = 0.98$, $p = 0.43$) revealed no significant effects on the latency of the pupillary light reflex. The latency of the pupillary light reflex did not change between the devices or over time (see *Table 5* below).

Discussion

In the present study we investigated possible effects of two different display types on various measures of attention, fatigue and visual strain. To this end we compared how reading on each device type in everyday-like conditions affects fatigue or strain over time. Statistically any difference would be as a result of an interaction of the factors device and time. In the following sections the findings are discussed for the different subjective and objective measures.

Fatigue

Subjective general fatigue significantly increased over time from test block 1 to 5. This could be expected, given that participants were required to perform focused reading interrupted by several test blocks during a total of approximately 4 h. There was also a difference based on the device, with higher fatigue ratings for the LCD-device. However since this difference was already present at the pretest (T0) before any interaction with the reading device this effect represents a difference in baseline fatigue which persisted over time. Since it is the only measure which showed this baseline effect, this may reflect a negative subjective bias towards reading on a tablet from the beginning of the experiment. Interestingly the *device* $\times$ *time*-interaction did not approach significance suggesting that general fatigue increased in a similar manner when reading on one or the other device. For visual fatigue neither the effects of time or device nor their interaction reached significance. To test for statistical power, a power analysis with an effect size of 0.7 was calculated with $n = 10$, $\alpha = 0.05$ and power $= 0.88$, revealing sufficient statistical power of the analysis conducted in this study. While, although not significant, visual fatigue tended to increase over time the data do not suggest any differences between the devices. The questionnaire used in the study[16] was not validated but was used in previous

Table 4. Mean fixation duration and proportion of regressive fixations. Standard deviations in brackets

	T0	T1	T2	T3	T4	Total mean
Mean fixation duration (in ms)						
e-Ink	205 (79)	215 (89)	208 (81)	201 (84)	197 (78)	205 (78)
LCD	209 (54)	201 (69)	212 (68)	185 (57)	211 (75)	204 (58)
Proportion of regressive fixations (in %)						
e-Ink	21.6 (7.1)	17.8 (6.3)	21.2 (8.0)	22.6 (9.8)	17.0 (5.4)	20.1 (6.0)
LCD	20.5 (7.2)	21.6 (6.6)	21.2 (5.8)	21.4 (6.6)	22.9 (8.8)	21.5 (6.6)

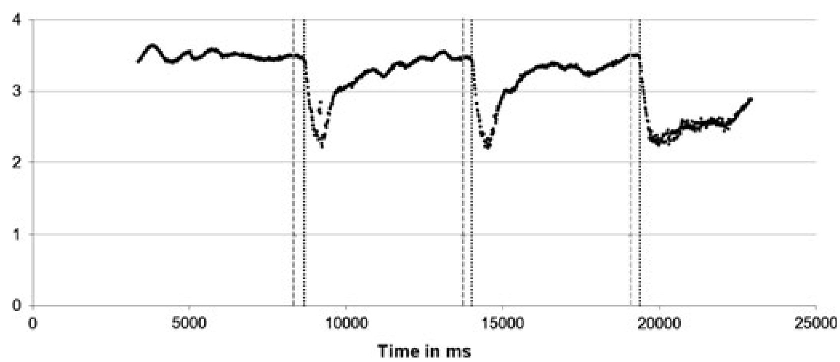

Figure 5. Illustration of the assessment of the pupillariy light reflex. The grey dashed line represents the onset of the flash, the black dotted line represents to onset of the pupillary reaction which was set by the experimenter during the offline analysis. The average from the three resulting latencies entered statistical analysis.

Table 5. Mean latency of the pupillary light reflex in milliseconds. Standard deviations in brackets

	T0	T1	T2	T3	T4	Total mean
Total Time (in ms)						
e-Ink	300 (38)	298 (31)	305 (51)	292 (38)	307 (39)	300 (24)
LCD	283 (36)	273 (26)	264 (65)	304 (48)	304 (44)	285 (22)

peer-reviewed studies.[17–20] It is possible that a more validated instrument would lead to different results, but since the questionnaire data suggested increased visual fatigue over time, as you might expect, this provides some indirect evidence for the validity of the questionnaire.

Also the latency of the pupillary light reflex was not differentially affected by the two reading devices. Previous studies show that pupillary light reflex is a useful measurement in visual fatigue and also in several contexts related to it (i.e. in the context of sleep deprivation.[13,21]) Therefore we suggest that the lack of any difference in the results from the two devices is not caused by the use of insensitive measurements. Since the other subjective and objective measures assessed in this study also did not reveal any differential effects of reading on the two different screen-types on fatigue, we propose that no differences in visual fatigue was present. Nevertheless, reliable data has to be provided by future research in order to validate the ability of the tests conducted in this study to differentiate between the two display technologies.

Due to the known problems in assessing fatigue with objective measures (see for example [14] for a critical discussion) we conducted a multi-method assessment of fatigue to be able to compare the different measures as well as to have different measures potentially measuring the same construct. Due to the fact that the data showed an increase of fatigue over time (within participants) and revealed no difference of fatigue-levels between devices, we assume that the measures conducted assessed changes in the fatigue. Nevertheless, further research should test for the sensitivity of these measures, since it could still be possible that the differences experienced by the participants were too small to be detected. If the differences were too small to be detected, though, it could be suggested that such small differences may not be relevant (i.e. what level of precision can be regarded as meaningful?).

Reading speed

On average, while reading easy text material such as prose, people read at a rate of 200–300 words per minute[22] similar to the results of the present study. Participants read an average of approximately 300 words per minute irrespective of the reading device and time within the experiment. The amount of text read within 45 min was very consistent and did not increase in the successive reading blocks.

Eye movements (regressive fixations)

The analysis of the two oculomotor parameters mean fixation duration and proportion of regressive fixations provided no indication of differential effects of the two devices. The significant *time* × *device* interaction with respect to regressive saccades resulted from differences between e-Ink and LCD in T1 and T4 rendering the interpretation in terms of fatigue inconclusive. If reading on one display type causes more fatigue one would expect a gradual increase of such a difference, but not in an early and late phase. Overall the oculomotor findings of the studied subject sample therefore suggest that reading on e-Ink and backlit LCD as tested in the present experiment does not have significant effects on oculomotor behaviour, at least for casual reading.

Visual search

Besides subjective and oculomotor measures, a letter search task was introduced as an additional performance task covering visuo-cognitive information processing. However data on visual search also revealed no differences between the devices in the total time needed, the number of hits or the mean time per hit.

Limitations of the study

The experiment was designed to achieve a high validity; the reading situation should be as real as possible. However, this approach brings with it some confounding variables. For example because participants were allowed to hold the reading device as they preferred, the reading distance was not fixed and controlled. Another limitation was the fixed artificial lighting conditions as we cannot transfer the results to outdoor daylight conditions.

To summarise, except for an unspecific effect on general fatigue, we have found no indication of any significant effect caused by the tested reading devices on either subjective or objective measures of attention or visual strain following reading over an extended period of time. We therefore conclude that reading from e-Ink or backlit LCD is comparable at least with the specifications used in the current devices and for the subject sample studied. Earlier findings of increased visual strain following reading on electronic devices may stem from the fact that these displays had relatively low resolution, contrast or refresh rates. Today, with increasing screen quality and current display characteristics these effects appear to vanish and in contrast to those early findings concerning reading on electronic displays, modern reading devices allow for comfortable reading and provide the possibility of adjusting font size, which (compared to reading on paper) represents an advantage for people with impaired vision. As Dillon[3] stated almost twenty years ago: 'Although reading from computer screens may be slower and occasionally less accurate […] It is almost certain that neither inherent problems with the technology nor the reader are causal factors. Invariably it is the quality of the image presented to the reader which is crucial'. Finally it should be kept in mind that, besides display characteristics, other factors such as the usability do also affect subjective readability and visual discomfort[23] in everyday life.

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Appendix

Visual strain questionnaire

(1) 'I have difficulties in seeing'; (2) 'I have a strange feeling around the eyes'; (3) 'Myeyes feel tired'; (4) 'I feel numb'; (5) 'I have a headache'; (6) 'I feel dizzy looking at the screen.'

We used a translated version in German. Each item was rated on a 10-point Likert scale for severity of discomfort, with '1' representing 'not at all' and '10'representing 'very much'.