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Eye movement analysis of reading from computer displays, eReaders and printed books

Daniela Zambarbieri and Elena Carniglia

Dipartimento di Ingegneria Industriale e dell'Informazione, University of Pavia, Pavia, Italy

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Correspondence: Daniela Zambarbieri
E-mail address: daniela.zambarbieri@unipv.it

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Abstract

Purpose: To compare eye movements during silent reading of three eBooks and a printed book. The three different eReading tools were a desktop PC, iPad tablet and Kindle eReader.

Methods: Video-oculographic technology was used for recording eye movements. In the case of reading from the computer display the recordings were made by a video camera placed below the computer screen, whereas for reading from the iPad tablet, eReader and printed book the recording system was worn by the subject and had two cameras: one for recording the movement of the eyes and the other for recording the scene in front of the subject.

Results: Data analysis provided quantitative information in terms of number of fixations, their duration, and the direction of the movement, the latter to distinguish between fixations and regressions. Mean fixation duration was different only in reading from the computer display, and was similar for the Tablet, eReader and printed book. The percentage of regressions with respect to the total amount of fixations was comparable for eReading tools and the printed book.

Conclusions: The analysis of eye movements during reading an eBook from different eReading tools suggests that subjects' reading behaviour is similar to reading from a printed book.

Introduction

During reading the eyes do not move in a continuous way but they make a sequence of alternating saccadic movements and fixations. Many studies can be found in the literature about the characteristics of eye movements in reading that are focused on fundamental aspects such as perceptual span,[1,2] landing position effects,[3,4] parafoveal-on-foveal effects,[5] word skipping,[6] word processing and identification.[7–10]

In addition a growing interest has developed about online reading due to the widespread use of computers in the office and in everyday life activities. The majority of studies are based on the reading speed,[11,12]comprehension,[13–15]proofreading accuracy,[16]and only a few make use of eye tracking methodology. Many physical characteristics have an influence on reading online such as font size, screen dimension, contrast and luminance, and line length (see Dillon[17] and Dyson[18] for extensive reviews).

In more recent years the interest of online reading studies has been attracted by an emerging area of application of information technology (IT), that of electronic publishing. An eBook, or 'electronic book', is a digital version of a book that can be read by using different devices that belong to two main categories: dedicated and non-dedicated devices. eReaders are dedicated devices designed primarily for the purpose of reading digital eBooks and most of them utilize e-paper technology, which is a non-backlit electronic display that simulates text printed on paper. Non-dedicated devices include desktop computers, notebooks, tablets and smartphones and they can be used for reading an eBook by means of specialized reading software. Taken together all these devices will be referred to within the paper as 'eReading tools'.

Compared to traditional paper books, eBooks present some advantages since they: (1) are easily updateable, for correcting errors and adding information; (2) are searchable – one can quickly find anything in the book; (3) can be annotated without harming the original work; (4) make reading accessible to persons with disabilities as text can be resized for the visually impaired, and read aloud; (5) can be hyper-linked, for easier access to additional information; (6) allow the option for the addition of multimedia, including still images, moving images, and sound.

Disadvantages could arise however from the level of usability and functionality of eReading tools. Making notes, bookmarks, highlights and turning pages back and forth on a printed book are all actions that everyone has learned to do since infancy. But doing the same actions by using a mouse, touchscreen or 5-way controller is quite different. In addition to interactivity aspects it is worth considering whether or not the normal reading behaviour can be affected and modified when eReading tools are used. In a study in which subjects were reading a novel from an iPad and Kindle, Nielsen[19] found 6.2% and 10.7% lower reading speeds for iPad and Kindle, respectively, compared to the printed book: 'we can say that tablets still haven't beaten the printed book: the difference between Kindle and the book was significant at the $p < 0.01$ level, and the difference between iPad and the book was marginally significant at $p = 0.06$'.[19] In two different studies, Siegenthaler *et al.* have compared reading behaviour between e-paper displays and print[20], and between e-paper readers and tablets.[21] Based on the syllogism of the transitive properties of equality they concluded that 'reading on an e-ink-reader is very similar to the reading process when reading a classic paper book (Siegenthaler *et al.*, 2011). Since the results in the present study show that reading on a tablet is not worse than reading on an e-ink-reader we can conclude that reading on a tablet is under artificial light conditions not worse than reading on a classic paper book'.[21]

Within this scenario, the aim of the present study was to compare eye movement behaviour during reading from three different eReading tools (desktop computer, tablet, e-paper reader) and from a printed book in experimental situations as close as possible to daily life conditions. In fact subjects were asked to read silently, at their own speed, one whole chapter from a book. The comparison was focused on fixations and regressions in terms of mean duration and percentage of occurrence, based on the assumption that these parameters being related to perceptual and/or cognitive processes in reading would reveal any important differences.

Methods

Experimental material

The Italian translation of *Three Men in a Boat (To Say Nothing of the Dog)* was chosen for the reading experiments. It is a comic novel by Jerome K. Jerome that is pleasant and engaging to read.

During the experiments, chapters from the novel were read in the printed edition and in eBook format. Three types of the most popular eReading tools were chosen: a desktop PC (http://www.asus.com), with a 17″ screen running the Adobe Digital Editions program that is the standard application for reading Adobe DRM protected ePub files; Apple iPad (http://www.apple.com) with BlueFire Reader application; Amazon Kindle (http://www.amazon.com) eReader that makes use of e-paper technology. The KindleDX model was used for the experiments since the display size is comparable to that of the iPad. Technical specifications for all tested conditions are summarized in Table 1. Text space on the screen, font type and font size are built into the software applications. While individual eReading tools allow certain modification of the font size, the default size was adopted and maintained throughout the study. The height of a lowercase letter u was measured instead of x-height, since the text was in Italian. eBook format makes use of the serif font, and the eReading tool sets the typeface. In all tested conditions the typeface was analogous to Times New Roman.

The luminance (cd m^{-2}) of the symbols (Ls) and the luminance of the immediately adjacent background (Lb) were measured using a MINOLTA LS 100 (http://www.konicaminolta.com) luminance meter, with acceptance angles of 1°. Luminance contrast was calculated using the Weber contrast formula given by contrast = (Ls−Lb)/Lb.

Eye movements recording

Eye movements were recorded by using the video-oculographic technique (VOG). VOG makes use of the image of the eye taken by a digital video camera and identifies the pupil and compute gaze direction. In order to make this data processing fast enough to be performed in real time, the eye is usually illuminated with infrared light to make the image of the pupil 'bright' and to create corneal reflexes (Purkinje images). Being invisible to the subject the infrared light does not create a distraction. The first among the four Purkinje images is the reflection from the front surface of the cornea; it has the highest intensity, and can be easily tracked. In order to adapt to the specific requirements of experimental protocols, different layouts of VOG recording systems are available: a fixed system in

Table 1. Technical specifications for all tested conditions

	Desktop Computer	iPad (1st generation)	Kindle DX	Printed Book
Screen	LCD 17″ 1280 × 1024 pixel	LCD 9.7″ 1024 × 768 pixel	e-paper 9.7″ 1200 × 824 pixel	–
Input mode	Mouse Keyboard	Touch screen Virtual keyboard	Keyboard 5-way controller	–
Device size	–	18.7 × 24.2 cm	18.3 × 26.4 cm	12.5 × 19.6 cm
Device weight	–	680 g	535 g	190 g
Display region	15.7 × 17.7 cm	7.8 × 14.1 cm	12.5 × 17 cm	8.5 × 15.6 cm
Font size	2.5 mm	2.3 mm	2.4 mm	2.1 mm
Symbol luminance (Ls, cd m^{-2})	2.7	7.6	4.6	3.2
Background luminance (Lb, cd m^{-2})	116.1	184.6	25.1	28.4
Weber Contrast CW = (Ls–Lb)/Lb	−0.98	−0.96	−0.82	−0.89

which the head is stabilized in front of the camera by using a chin rest or a bite bar; a head mounted or wearable system that is fixed to the head and a remote system usually placed below or within the computer display. The head mounted devices can be equipped with an additional camera that can record the scene in front of the subject.

For the experiments described in this paper two recording devices were used: *EyeGaze* (LC Technologies, http://www.eyegaze.com) and *MobileEye* (ASL Applied Science Laboratories, http://www.asleyetracking.com). With the EyeGaze system, gazepoint tracking measurements are made unobtrusively via a remote video camera mounted below the computer display. EyeGaze uses the Pupil-Centre/Corneal-Reflection method to determine gaze direction. A small, low power, infrared light emitting diode (LED) located at the centre of the camera lens illuminates the eye. The safety factor of the LED is 5 as at a range of 45 cm the LED illumination on the eye is 20% of the HEW (Department of Health, Education, and Welfare of United States of America) max permissible exposure. The LED generates the corneal reflection and causes the bright pupil effect, which enhances the camera's image of the pupil. Specialized image-processing software identifies and locates the centres of both the pupil and the corneal reflection. Trigonometric calculations project the person's gazepoint based on the positions of the pupil centre and the corneal reflection within the video image. The sampling rate is 60 Hz.

The MobileEye system is a head mounted VOG device. The lightweight frame supports two digital cameras, one that records the scene image and the other the subject's eye. These images are then integrated into a single video recording representing the scene with a superimposed gaze cursor. The MobileEye uses the Dark Pupil Tracking technique. A set of three harmless infrared lights is projected on the eye and reflected by the cornea appearing to the camera as a triangle of three dots at a fixed distance from each other. When the eye turns, the centre of the pupil will move relative to the head. However, due to properties of the cornea, the corneal reflection remains approximately in the same position relative to the head. Therefore, by comparing the vector (angle and distance) between the pupil and the cornea, the eye tracking system identifies the direction of gaze. The sampling rate is 30 Hz for each digital camera.

Experimental Protocols

At the beginning of the experiment the subject was informed about the nature of the study and was asked to read and sign the informed consent to participate in the experiments. The study followed the tenets of the latest declaration of Helsinki.

Protocol 1.
The subject was seated at the desk, about 60 cm from the computer display; the EyeGaze system was positioned below the computer display and the camera lens was adjusted to focus the subject's eye and to centre the pupil and the corneal reflex. During calibration the subject was asked to look at a series of dots sequentially displayed at different locations on the screen, and to keep fixation stable until the appearance of the next dot. After calibration, the subject was asked to read Chapter 1 of the eBook by means of the Adobe Digital Editions program.

Protocol 2.
The subject was seated at the desk, and the MobileEye system was placed on the subject's head and the transparent mirror was pitched and/or twisted for adjustment of the image within the camera field. During calibration the subject was asked to fixate specific points in front of him/her and the corresponding position on the screen was identified by the operator with a click of the mouse. After

calibration the subject was asked to read Chapter 2 of the eBook by using the BlueFire Reader iPad application.

Protocol 3.
As in Protocol 2 the MobileEye device was used to record eye movements, following the same adjustment and calibration steps. The subject was asked to read Chapter 3 from the printed edition of the book.

Protocol 4.
As in Protocols 2 and 3, the MobileEye device was used to record eye movements, following the same adjustment and calibration steps. Amazon KindleDX was used; after calibration the subject was asked to read Chapter 4 of the eBook.

All experiments were carried on in a room illuminated from an overhead light source. The total duration of the experiments ranged between 12 and 15 min. In Protocols 2, 3, and 4, that made use of the MobileEye recording device, the subject was free to hold the eReading tool either resting his/her arms on the desk or keeping the eReading tool on his/her knees. Nevertheless before starting the recording session the subject was asked to find a comfortable posture, checking for a distance from the device close to 60 cm, and to maintain it throughout the experiment. Although the sampling rate is different from that of MobileEye, the use of EyeGaze in Protocol 1 was preferred in order to allow the subject to maintain a natural reading posture in front of the screen.

Subjects

Fifteen subjects were examined within each experimental protocol. Subjects were university students or post-doctoral researchers with good familiarity with computers and Web navigation but not regular eBook readers. All subjects had normal vision or corrected-to-normal by means of contact lenses and none required spectacles during testing. A few subjects were tested in two different protocols, randomly selected. The reason for that is simply due to the fact that most of the students and researchers at the Faculty had corrective glasses and wearable VOG recording systems are not compatible with them. In total the examined population included 43 subjects (16 males and 27 females) aged between 22 and 32 years (mean = 24.4 ± 2.6 years).

Data analysis

When studying visual exploration behaviour a two-dimensional analysis of eye movements is conducted by considering the scanpath of the eye and by computing metrics within specific areas of interest. Instead the analysis of eye movements during reading is based on the temporal evolution of horizontal components of the eye movement. During reading the eyes move from left to right by making saccadic movements followed by fixations. Sometimes a saccade from right to left is observed when the eyes go back to look at material that has already been read (*regression*). When reaching the end of the line the eyes make a large leftward saccade (*return sweep*) with a small vertical component in order to reach the beginning of the next line.

Both recording devices used in the experiments provide raw data in terms of horizontal and vertical position of the eyes with respect to the computer screen (EyeGaze) or with respect to the scene taken by the second camera on the frame (MobileEye). Interactive software has been developed in our laboratory for reading analysis from the raw data. The first step in the analysis of eye movements is the identification of all saccadic eye movements by means of a velocity threshold algorithm. Saccade beginning is identified as the time when eye velocity exceeds the threshold; the time when eye velocity returns to values lower than the threshold is recognized as saccade end.[22,23] The velocity threshold is chosen by the experimenter depending on the noise level of the signal and the resolution of the recording device. Normally the threshold corresponds to $15° s^{-1}$. Another threshold is used by the program to identify, within leftward saccades, the return sweeps that, being of greater amplitude reaches much greater peak velocity compared to saccades during reading. Return sweep threshold is normally about $50° s^{-1}$.

Once saccades and return sweeps have been identified the intervals of time between two successive saccades are computed and classified as fixation or regression. Since the present study gave priority to maintaining the experimental conditions as close as possible to the natural situation no constraints were used to keep the subject's head fixed. Subjects were free to move the head, or the device up and down when reading. By consequence saccade parameters were not considered in data analysis due to the lack of reliability of pixels to degrees transformation.

Experiments are designed as between-subjects. Statistical analysis has been conducted by means of one-way ANOVA ($\alpha < 0.05$) and post-hoc tests were performed by using t-tests ($\alpha < 0.05$).

Results

The presentation of experimental results will focus on two aspects of reading behaviour: mean duration of fixations and regressions, and percentage of regressions with respect to the number of progressive fixations.

Table 2. Mean duration (ms) and standard deviation (SD) of fixations and regressions in the four experimental protocols

	Fixation duration (ms)		Regression duration (ms)	
	Mean	**SD**	**Mean**	**SD**
PC	223.5	84.8	199.8	82.2
iPad	208.4	92.1	207.1	94.5
KindleDX	201.5	85.9	183.6	84.1
Book	215.8	92.1	196.4	86.5

Fixation duration

Since vision is suppressed during saccade execution, it is only during fixations that the central nervous system can elaborate visual information. Thus fixation duration is a well-established indicator of the difficulty of perceptual and/or cognitive processing in reading.[10,24,25] The mean duration of fixations and regressions in the four experimental protocols are summarized in Table 2.

Mean fixation duration was significantly different among PC, iPad, Kindle and book reading ($F_{3,56} = 3.48$, $p = 0.02$). The results from the post-hoc test based on t-tests are summarized in Table 3. Significant differences were found between PC and iPad and between PC and KindleDX. However, mean fixation durations for iPad and KindleDX were not different from those with the printed book. These eReading tools are 'hand in', that means that the subject has the reading device in his/her hands as it normally happens in everyday life reading from printed material, in a more comfortable situation with respect to reading from the PC display sitting at the desk.

Regressions duration

The mean duration of regressions was significantly different between the PC, iPad, Kindle and book reading ($F_{3,56} = 4.9$, $p = 0.004$). From the post-hoc tests (Table 3) it emerged that the KindleDX produced different regression durations. Within the same experimental protocol the mean duration of fixations was different from that of regressions ($p < 0.05$) except for the iPad. In this protocol there was no statistical difference in mean duration between fixations and regression ($p = 0.94$).

Number of regressions

An interesting aspect to be considered among the experimental results for quantitative evaluation of oculomotor behaviour is related to the frequency of occurrence of regressive movements. A regression is made to go back to a previously read part of text and is likely to be related to perception and/or comprehension difficulties. In adult normal readers regressive saccades represent about 15% of all saccades.[26,27]

The mean percentage of regressions with respect to the total number of fixations in the four experimental protocols was found to be 13%, 10%, 13%, 11%, respectively and ANOVA indicated no statistically significant differences ($F_{3,56} = 2.6$, $p = 0.06$).

Discussion

As explained in the introduction, the analysis of eye movements during reading from different eReading tools and from printed book focused on progressive fixations and regressions. Mean fixation duration was longer in reading from the computer display, whereas tablet and eReader did not differ from the printed book. Significant differences were found in regression mean duration when reading from KindleDX, and this result is quite surprising since the KindleDX display makes use of e-paper technology that is supposed to be the most similar to printed paper.

Table 3. *t*-test comparison of mean durations within the four experimental protocols. Asterisk indicate significant different values ($p < 0.05$)

	PC	**iPad**	**Kindle DX**	**Printed book**
Fixation durations				
PC	–	$p = 0.04$*	$p = 0.0005$*	$p = 0.12$
iPad	$p = 0.04$*	–	$p = 0.43$	$p = 0.45$
Kindle DX	$p = 0.0005$*	$p = 0.43$	–	$p = 0.07$
Printed book	$p = 0.12$	$p = 0.45$	$p = 0.07$	–
Regression durations				
PC	–	$p = 0.14$	$p = 0.012$*	$p = 0.99$
iPad	$p = 0.14$	–	$p = 0.002$*	$p = 0.25$
Kindle DX	$p = 0.012$*	$p = 0.002$*	–	$p = 0.04$*
Printed book	$p = 0.99$	$p = 0.25$	$p = 0.04$*	–

Siegenthaler *et al.*[20] have compared reading processes on e-paper displays (The reading devices used in their study were: iRex iLiad, Booken Cybook, BeBook, Sony PRS-505, ECTACO jetBook.) vs print and found significant differences in fixation duration. however, in their study subjects could choose the font size that was most comfortable for them, and this resulted in quite different page layouts. In a more recent study the same authors compared reading behaviour on iPad and two models of Sony Reader (PRS-505 and PRS-600) with e-paper display. In this study the font size was kept constant (although the iPad display was greater than the Sony eReaders display) and no significant difference in fixation duration was found.[21]

In considering the results reported in Table 2 and 3 note that even in those cases in which statistically significant differences were found, these differences (in the order of 10–20 ms) are small and comparable to the resolution time of the recording devices. More consistent data are those related to the number of progressive fixations and regressions, since these parameters are not affected by the sampling rate. No significant difference was found in the percentage of regressions for all test conditions and the values are consistent with those reported in the literature for normal reading in adult subjects.[27]

The evaluation of the oculomotor behaviour during reading eBooks has been conducted by creating an experimental set up as close as possible to real life situations, and subjects were free to read at their own speed, and they read a whole chapter of a novel. Thus, the results described in this paper further confirm and complete similar studies on reading behavior.[20,21] Reading an eBook from different eReading tools and reading from a printed version do not differ significantly in terms of oculomotor behaviour. Since fixation duration and percentage of regressions are related to reading difficulties[24–27] it is reasonable to assume that reading an eBook through an eReading tool is not more difficult or uncomfortable than reading a printed book.

As indicated in the introduction, eBooks and eReaders represent a technological revolution which, while not claiming to replace the more traditional printing on paper, can bring great benefits to many aspects of reading, particularly for textbooks and in learning environments where the addition of multimedia can be a major advantage. Hyperlinks and hierarchical organization of the contents can improve learning performance and the possibilities offered by eReader tools to change the font size and offer audio represent a great advantage for visually impaired people and for the older population. Finally, the storage capabilities of eReaders and tablets add further benefit to the use of these technologies.

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