Eye movements, convergence distance and pupil-size when reading from smartphone, computer, print and tablet

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Abstract

The purpose of this study was twofold: to investigate visual parameters when reading from digital devices and paper in free-viewing conditions and to evaluate the utility of eye tracking glasses to assess visual parameters under different settings. The Tobii Pro Glasses were used to monitor visual parameters of 20 subjects whose visual acuity was 1.0 or better in both eyes. Subjects were asked to read texts from the IReST-test. The task was performed at the participant's preferred reading distance on a smartphone, computer, tablet and paper. Reading was measured twice with a 60 minute break between sessions. Each participant read 8 different texts, the sequence for texts and devices was randomized. Differences were found between devices for saccade amplitude, fixation duration, convergence distance and pupil size. The computer and tablet revealed the largest difference in reading speed (8 words-per-minute). Pupil size was reduced up to 20% across all digital devices compared to print. Changes in visual parameters observed whilst reading from different devices may reflect an attempt from readers to optimize performance. The need to maintain visual performance under different visual condition may lead to increased visual symptoms. Eye-tracking glasses may be a reliable tool to investigate aspects of visual discomfort when using digital devices.

Sammendrag

Formålet med denne studien var todelt: å undersøke visuelle parametere ved lesing av tekst på elektroniske skjermer versus papir under naturlige forhold og å evaluere bruken av briller som måler øyebevegelser for å studere visuelle parametere under ulike forhold. Tobii-Pro briller ble brukt til å måle øyebevegelser hos 20 deltakere med visus 1.0 eller bedre i begge øyne. Deltaker ble bedt om å lese fra IReST-testen. Oppgaven ble utført på deltakerens foretrukne leseavstand med smarttelefon, datamaskin, nettbrett og papir. Lesehastighet ble målt 2 ganger med 60 minutters pause mellom målingene. Hver deltaker leste 8 ulike tekster, rekkefølgen av tekstene og skjermene var tilfeldig. Forskjeller ble funnet mellom de ulike leseoppgavene for sakkadisk amplitude, fiksasjonsvarighet, konvergensavstand og pupillestørrelse. En liten forskjell i lesehastighet ble funnet mellom datamaskin og nettbrett (8 ord pr. minutt). Pupillestørrelsen var opp til 20% mindre ved bruk av skjermer i forhold til lesing av tekst trykt på papir. Forskjeller i visuelle parametere ved lesing på ulike skjermer versus papir kan reflektere forsøk på å lese best mulig. Behovet for å opprettholde visuell prestasjon ved lesing av tekst på ulike skjermer versus papir kan forårsake økt synsubehag og symptomer. Briller som måler øyebevegelser kan være et verdifullt verktøy for å undersøke personer som opplever synsubehag ved skjermbruk.

Introduction

Reading from screens has become a necessity in the current digital context. A considerable amount of reading is performed on displays, such as computer screens, smartphones and tablets. The extensive use of these devices has been associated with symptoms of visual discomfort. These symptoms occur in the absence of specific causes and have been defined by the scientific community as "computer vision syndrome", also known as digital eye strain (Blehm, Vishnu, Khattak, Mitra, & Yee, 2005; Myrberg & Wiberg, 2015; Sheppard & Wolffsohn, 2018). Visual discomfort can have significant impact on daily activities (Hayes, Sheedy, Stelmack, & Heaney, 2007) and is likely to be caused by a combination of prolonged use of displays, oculomotor anomalies and inefficient lubrication of the ocular surface of the eye (Rosenfield, 2011). The use of digital devices, with difference screen sizes, leads to the adoption of atypical reading distances and changes in visual parameters that need investigation. For example, short reading distances can increase fixation disparity (vergence errors). Some amount of fixation disparity is tolerated during reading but frequent changes in disparity may require more effort during the execution of eye movements (Jainta, Blythe, Nikolova, Jones, & Liversedge, 2015).

The characterization of reading distances and other visual parameters during reading such as pupil size or blinking rate have been investigated using laborious and error prone methods (Argiles, Cardona, Perez-Cabre, & Rodriguez, 2015; Rosenfield, Jahan, Nunez, & Chan, 2015). Wearable eye tracking glasses can be used for monitoring several visual parameters under unrestricted conditions when using digital devices (Tobii, 2017). The purpose of this study was twofold: to investigate visual parameters when reading from digital devices and paper in free-viewing conditions and to evaluate the utility of eye tracking glasses to assess visual parameters under different settings. The methods described in this manuscript may be of interest when investigating, for example, visual discomfort caused by the use of displays (also known as: computer vision syndrome or digital eyestrain).

Methods

Participants

Twenty adults participated in this study, 50% females, the mean age was 30 years ($SD = 5$), all had unaided or best corrected (corrected with contact lens) visual acuity of 1.0 in both eyes and passed a binocular fusion test. Participants were required to have a minimum of six years of school education.

Texts and devices

Eight out of 10 texts of the International Reading Speed Test (IReST) (Macedo & Silva, 2013; Trauzettel-Klosinski & Dietz, 2012), were assigned, in random sequence, to a code consisting of participant-device-session. For example, for participant 1 the following codes were generated: 1116, 1124, 1132, 1145 and 1211, 1227, 1238, 1243. The first character is the participant, second is the session, third is the device and the fourth is the text. The characteristics of the digital devices used are given in Table 1.

The sequence generated, as given above, was randomized within each session, for example, participant 1 in session 1 read: 1132 (print), 1124 (computer), 1116 (smartphone), 1145 (tablet). The format of the original test was modified to fit all displays. The limitations were imposed by the smartphone; the font size was reduced from 10- to 9-point in the digital devices. The print version was kept at 10-points similar to the original version of the test, only the number of rows (lines) were adjusted. Keeping

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the original size of the font allowed for a better comparison between our results and the normative information available for the test, the increment in the number of lines was necessary in order to compare print with the digital devices. The extra lines may have caused a small reduction in reading speed in the current study when compared with the normative values (Macedo & Silva, 2013). The font was Monospaced Courier New on all digital devices.

Table 1: *Characteristics of the devices used for reading. W-width; H-height.*

Device specifications / type	Smartphone	Computer	Tablet
Screen type and size (inch)	HD LCD 4.8	HD LCD 15	HD LCD 10.1
Resolution (pixel) (landscape)	1280×720	1366×768	1280×800
Input mode	Touch screen	Keyboard	Touch screen
Device size (mm)			
(landscape mode)	W136×H70	W381×H247	W259×H177
Device weight (g)	133	2280	800
Max. luminance (cd/m^2)	216	116	209
Min. luminance (cd/m^2)	2.9	2.6	3.1
Model	Samsung G850T	HP Pavilion 15-E027 Core	Toshiba WT10-A32 (Encore2)

Data recording and analysis

During recordings participants were seated with access to the reading devices, the experimenter (first author) gave instructions and controlled the order in which devices should be used. The illuminance in the room and the luminance of the displays were measured and maintained in all recording sessions. Participants were asked to read aloud to ensure that they were effectively performing the task and to allow comparison of speeds with the normative values (Macedo & Silva, 2013; Trauzettel-Klosinski & Dietz, 2012). Each text took approximately 1 minute to read, for an example look at the video provided here: https://www.dropbox.com/s/pwhkmcvhobft2ax/read_from_mobile_2.mp4?dl=0+. Subjects performed two reading sessions with a 60 minute break between them (session = a sequence of four texts read from four devices). The two sessions were defined to evaluate the consistency of the measurements, that is, to understand whether performing the task twice can lead to consistent changes in the outcome.

Reading parameters were monitored using the Tobii Pro Glasses controlled by the Tobii Glasses Controller Software (Glasses are shown in Figure 1 and Figure 2). The glasses are a wearable device that tracks the eyes movements using binocular corneal reflection with a sampling frequency of 50Hz and automatic parallax compensation. Before each session, the glasses were calibrated according to the user manual. Recording was paused when changing devices. Displays were uncovered only after pressing the recording button; this avoided the participant starting to read while preparing to hold the device. The reading distance was chosen freely by each participant for each device, participants were instructed to keep the distance as constant as possible during the task.

Saccade amplitude in degrees (angle α in Figure 1) was computed using the following equations (Hossain & Miléus, 2016):

$$\mathbf{a} = g(t_1) - p(t_1), \quad \mathbf{b} = g(t_2) - p(t_2), \quad \mathbf{c} = g(t_2) - g(t_1)$$

$$\alpha = \cos^{-1}\left(\frac{a^2 + b^2 - c^2}{2ab}\right) \tag{1}$$

where $g(t)$ and $p(t)$ are the gaze position and pupil position at time t, respectively. As shown in Figure 1, t_1 was the starting time for a saccade and t_2 was the end time; $g(t_1)$ was the gaze position at time t_1 and $g(t_2)$ was the gaze position at time t_2.

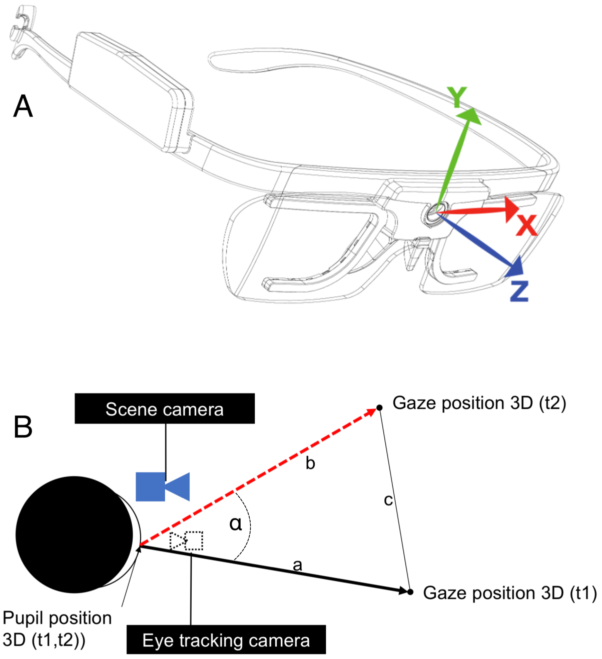

Figure 1: *Example of the geometry involved to compute saccade amplitude and convergence position. Image A shows the scene camera mounted in the eye tracking glasses, the scene camera is the origin of the 3D coordinates, eye tracking cameras are mounted in the lower part of the frame. Image B shows the angle alpha that provides the amplitude of the eye movements between two instants and can be computed using equation 1. The convergence distance is provided by the Tobii Glasses Analysis Software as the Z-coordinate (see A), in millimetres, of the gaze position. Of note, the distance scene camera-pupil is not included in Z-coordinate and its value is normally between 30 mm and 35 mm.*

Recorded files were analysed with the Tobii Glasses Analysis Software to detect events (saccades and fixations) during reading. Saccades were separated from fixations using a default value for the "velocity threshold" parameter of 30°/s (Olsen, 2012), a commonly used criteria also found in other eye tracking systems (Macedo, Crossland, & Rubin, 2011). Convergence distance (the point in space where the line of sight of both eyes cross) was obtained from the 3D position of the gaze provided by the glasses. Figure 2 shows several examples of the data extraction performed with the Tobii Pro software. Repeated measures were analysed using linear mixed models (LMM) (IBM SPSS, v24, Chicago, Illinois), a robust alternative to ANOVA recommended for analysis of repeated measures in small samples (Ferreira et al., 2017; Macedo, Crossland, & Rubin, 2008; Santos, Abrantes, Lewis, & Macedo, 2018). The normality of the variables was investigated with Kolmogorov-Smirnov and Shapiro-Wilk tests. The result from the normality test showed that the variables were normally distributed, and therefore LMM analysis was performed. The estimated marginal means (EMM) are a result of the LMM and represent an estimation of the mean value of the variable of interest after considering all the factors in the model.

Results

The main results of this experiment were reading speed, reading distance (convergence) and pupil size measured when reading with different devices. Figure 2 shows examples of the gaze behaviour during reading from the devices.

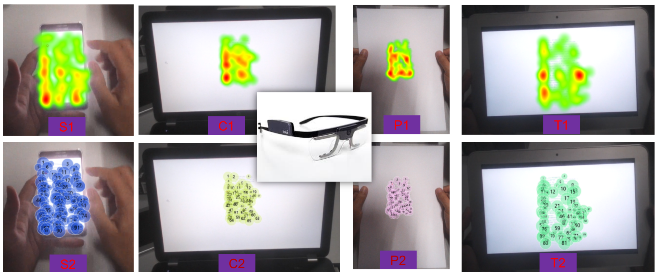

Figure 2: *Images of the devices used. The top row shows the heatmap generated by the Tobii Pro software overlapped with the text for (from left to right) smartphone, computer, print and tablet. The bottom row shows the same images with the fixations overlapped with the text in each device. The image of the glasses at the centre was retrieved from Tobii (Tobii, 2017). A Video of the subject performing the task can be found here: https://www.dropbox.com/s/pwhkmcvhobft2ax/read_from_mobile_2.mp4?dl=0.*

Reading speed

Table 2 summarizes the descriptive values for reading speed for each device and Figure 3 shows the summary per session. Reading speed values are in agreement with the results of previous studies (Ramulu, Swenor, Jefferys, & Rubin, 2013) but below the normative values of the test (Trauzettel-Klosinski & Dietz, 2012). The reason for this small reduction in speed has been explained in methods.

Table 2: *Summary of raw values of reading speed in words-per-minute (wpm). SE = standard error, IQR = interquartile range.*

	Smartphone (wpm)	Computer (wpm)	Print (wpm)	Tablet (wpm)
Mean (*SE*)	168.2 (3.2)	161.9 (3.1)	164.3 (3.1)	170.2 (3.3)
Median (IQR)	165.8 (31.6)	158.9 (27.1)	163.5 (17.8)	165.3 (23.0)

Using LMM we performed a within-subject analysis with fixed effects (session and device), we found statistically significant effects for device ($F(3, 131) = 3.1; p = 0.030$) and session ($F(1, 131) = 14.1; p < 0.001$). The mean difference between session was 8 wpm. Pairwise comparisons between devices revealed that there was a statistically significant difference between computer and tablet (mean difference = 8 wpm ($SE = 3$), $p = 0.049$).

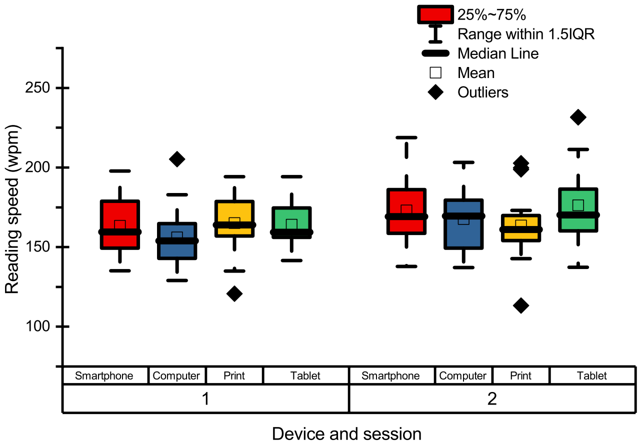

Figure 3: *Descriptive values of the reading speed per session and device.*

Eye movements

Table 3 summarizes the eye movement parameters analysed. Before computing descriptive statistics and performing the statistical analysis, some events (saccades and fixations) were excluded. We excluded saccades with more than 3.5 degrees of amplitude and fixations with more than 1 second of duration. Results for fixation duration and saccade amplitude are in agreement with previous studies (Jainta et al., 2015; Rayner, 1998; Vorstius, Radach, & Lonigan, 2014; Zambarbieri & Carniglia, 2012).

Table 3: *Descriptive statistics for eye movements in each device.*

	Saccade amplitude (degrees)		Fixation duration (ms)		Convergence distance (mm)	
	Mean	*SE*	Mean	*SE*	Mean	*SE*
Smartphone	1.40	0.04	282.3	12.2	226.8	9.4
Computer	1.26	0.05	353.5	14.3	288.6	14.9
Print	1.40	0.05	308.7	13.2	236.8	11.8
Tablet	1.32	0.04	284.0	12.9	237.8	11.0

Saccades during reading

Figure 4 shows the summary of saccade amplitude per session for each device. A model (LMM) with fixed effects session and device was run and we found statistically significant effects for device ($F(3, 131) = 3.4; p = 0.009$).

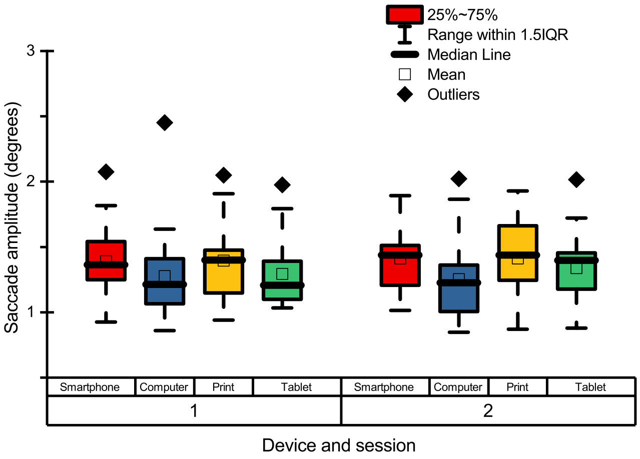

Figure 4: *Descriptive values of saccade amplitude per session and device.*

Pairwise comparisons between devices, summarized in Table 4, revealed that there was a statistically significant difference between computer and smartphone and print.

Table 4: *Differences of EMM for saccade amplitude between devices. The mean difference (SE) represents the difference between values for the device in the first column minus the device in the other columns. Negative values indicate smaller values were obtained for the device in the first column.*

	Smartphone	Print	Tablet
Computer	−0.14 deg (0.05) $p = 0.030$	−0.14 deg (0.05) $p = 0.029$	0.05 deg (0.05) $p = 1.000$

Fixation duration

Figure 5 shows the summary of fixation duration, in milliseconds, per session for each device. We changed the dependent variable and ran the same LMM referred for saccade amplitude. We found statistically significant effects for device ($F(3, 131) = 14.3; p < 0.001$) and session ($F(1, 131) = 6.7; p = 0.011$).

Pairwise comparisons between devices, summarized in Table 5, revealed that there was a statistically significant difference between computer and all other devices. The mean difference between sessions was 23 ms ($SE = 9$), $p = 0.011$.

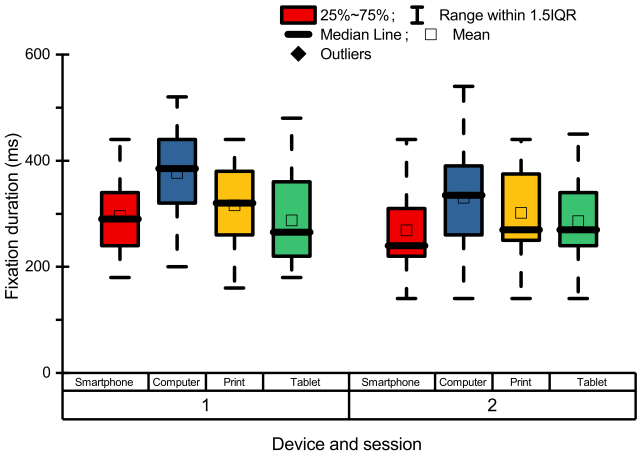

Figure 5: *Descriptive values of fixation duration per session and device.*

Table 5: *Difference of EMM for fixation duration between computer and other devices. The mean difference (SE) represents the difference between values for the device in the first column minus the device in the other columns.*

	Smartphone	Print	Tablet
Computer	71 ms (12) $p < 0.001$	46 ms (13) $p = 0.002$	70 ms (13) $p < 0.001$

Convergence Distance

Figure 6 shows the summary of convergence distance, in millimetres, per session for each device. With convergence distance as dependent variable, the LMM found statistically significant effects for device ($F(3,131) = 16.2; p < 0.001$) and session ($F(1,131) = 7.8; p = 0.006$).

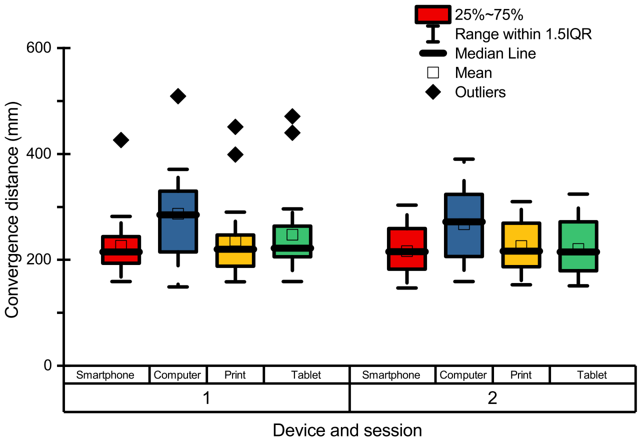

Figure 6: *Descriptive values of convergence distance per session and device.*

Pairwise comparisons between devices, summarized in Table 6, revealed that there was a statistically significant difference between computer and all other devices. The mean difference between sessions was 19mm ($SE = 7$), $p = 0.006$.

Table 6: *Difference of EMM for convergence distance between devices. The mean difference (SE) represents the difference between values for the device in the first column minus the device in the other columns.*

	Smartphone	Print	Tablet
Computer	62 mm (10) $p < 0.001$	53 mm (10) $p < 0.001$	50 mm (10) $p < 0.001$

Pupil size

Figure 7 shows the summary of pupil size, in millimetres, per session, eye and for each device. Data show a clear trend, that is, pupil sizes reduced in the case of digital devices when compared with print. For the final LMM "eye" was included as a fixed factor, that is, as a within-subject factor.

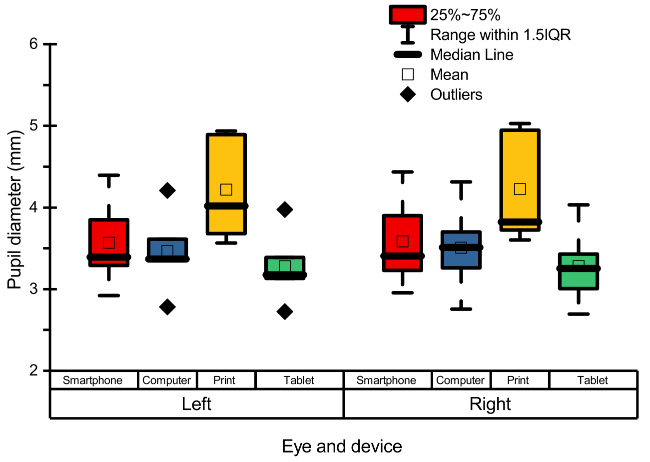

Figure 7: *Descriptive values of pupil diameter obtained per eye and device.*

There was an effect of type of device in pupil size, $F(3,293) = 194, p < 0.001$. The estimated marginal means were: smartphone = 3.40 mm ($SE = 0.11$), computer = 3.31 mm ($SE = 0.11$), print = 3.98 mm ($SE = 0.11$), and tablet = 3.17 mm ($SE = 0.11$). Pairwise comparisons between devices are summarized in Table 7.

Table 7: *Differences of EMM for pupil size between devices. The mean difference (SE) represents the difference between values for the device in the first column minus the device in the other columns. Negative values indicate smaller values were obtained for the device in the first column.*

	Computer	Print	Tablet
Smartphone	0.10 mm (0.035) $p = 0.046$	−0.58 mm (0.036) $p < 0.001$	0.23 mm (0.035) $p < 0.001$
Computer		−0.67mm (0.036) $p < 0.001$	0.13 mm (0.035) $p = 0.001$
Print			0.80 mm (0.036) $p < 0.001$

Discussion and conclusion

Results of our exploratory study indicate that reading speed for short texts, with similar font size, was only marginally reduced on the computer when compared with the tablet. This difference may be explained by the lower quality of the computer display (less contrast and lower resolution (pixels-per-inch)) when compared with, for example, the tablet (Köpper, Mayr, & Buchner, 2016). Michelson contrast on the computer screen was lower than in other devices and poor contrast is known to affect reading speed (Legge, Rubin, & Luebker, 1987). The lower performance is consistent with the prolonged fixation durations measured for computer reading. Also, as others have shown, the print size might affect performance and (as would be the case for the longer reading distance used for the computer) a reduced visual angle of the font can cause reduction in performance (Kochurova, Portello, & Rosenfield, 2015).

The typical reading distance was longer for the computer which indicates that devices with smaller screens are naturally held closer even when visual resolution (defined by font size) required to read is controlled. Shorter reading distances lead to larger saccades. The amplitude measured in degrees of visual angle is expected to increase with the proximity of the text when the saccade covers a similar number of characters, with a corresponding shorter fixation duration. The reduction in reading distance (more convergence required) is likely to have implications for the intensity of symptoms reported in cases of digital eye strain (Collier & Rosenfield, 2011). However, whether changes in fixation duration and saccade amplitude are markers for those at risk of symptoms of digital eye strain remains to be studied. Reading from computer screens with longer reading distances will reduce the demand on accommodation and convergence and is likely to be more comfortable for prolonged reading tasks than some of the other devices.

When compared with print, pupil size was reduced up to 20% when using digital devices. Pupil size is likely to change due to a variety of aspects from visual to cognitive. During visual tasks pupil size changes with the luminance of the screen, but also with the cognitive demands of the task (Just, Carpenter, & Miyake, 2003). Whilst increased luminance produced by screens reduces pupil size, as our study shows, cognitive demands are expected to increase pupil diameter with a peak diameter reached approximately 1200 ms after the onset of the demand (Beatty, 1982). Therefore, we speculate that when reading from screens instead of paper, under similar cognitive demands, the task is more likely to cause visual stress due to conflicting signals from different visual mechanisms. That is, the cognitive task demands dilation of pupil but, because screens are brighter than paper, the pupil flexibility to oscillate will be more limited. Conversely, smaller pupil diameters are likely to reduce optical defects and can eventually lead to better comfort. Further research needs to be conducted to disentangle these mechanisms.

The use of eye tracking glasses for studying visual parameters still has limitations. The algorithms used to separate fixations from saccades need refinements to reduce possible errors when detecting events (Hossain & Miléus, 2016; Olsen, 2012). Algorithms for data extraction should also provide reliable information about blink rate, which can sometimes be confounded with video signal loss of the cameras. Given the exploratory nature of the current study the number of participants was not defined according to any effect size which may reduce the generality of our conclusions. We also need to acknowledge that the size of the margins, which are different in different devices, may have had an effect on reading speed that was uncontrolled in the current study (Youngman & Scharff, 1998).

In summary, monitoring visual parameters in natural conditions is likely to provide further understanding of the underlying causes of visual discomfort during visual tasks, e.g. digital eye strain. Our study also shows that eye tracking glasses are a powerful tool for investigating visual parameters during highly demanding visual tasks such as reading from screens.

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