Smaller pupil size and better proofreading performance with positive than with negative polarity displays

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Abstract

The “positive polarity advantage” describes the fact that reading performance is better for dark text on light background (positive polarity) than for light text on dark background (negative polarity). We investigated the underlying mechanism by assessing pupil size and proofreading performance when reading positive and negative polarity texts. In particular, we tested the display luminance hypothesis which postulates that the typically greater brightness of positive compared to negative polarity displays leads to smaller pupil sizes and, hence, a sharper retinal image and better perception of detail. Indeed, pupil sizes were smaller and proofreading performance was better with positive than with negative polarity displays. The results are compatible with the hypothesis that the positive polarity advantage is an effect of display luminance. Limitations of the study are being discussed.

Keywords

display polarity, pupil size, eye tracking, display design, screen luminance

Practitioner Summary

Digital displays are ubiquitous. Understanding of the mechanisms underlying the perception of text is important for good display design. The hypothesis that bright positive polarity displays lead to small pupils and a sharp retinal image which improves reading cannot be rejected and is thus maintained. Positive polarity displays are recommended.

Smaller pupil size and better proofreading performance with positive than with negative polarity displays

1. Introduction

Text can be presented in dark characters on light background (positive polarity) or in light characters on dark background (negative polarity). The presentation of dark characters on light background may also be referred to as negative contrast because contrast $c = (L_t - L_b)/(L_t + L_b)$ turns negative if text luminance, L_t, is lower than background luminance, L_b. A brief review of research on the legibility of positive compared to negative polarity texts reveals an interesting mix of findings. On the one hand, several studies showed that text presented in positive polarity leads to better legibility and higher visual comfort than light characters on dark background (e.g., Bauer & Cavonius, 1980; Buchner & Baumgartner, 2007; Chan & Lee, 2005; Mayr & Buchner, 2010; Piepenbrock, Mayr, & Buchner, in press; Piepenbrock, Mayr, Mund, & Buchner, 2013; Radl, 1980; Taptagaporn & Saito, 1990, 1993; Tsang, Chan, & Yu, 2012). On the other hand, findings of no positive polarity advantage have also been reported (e.g., Creed, Dennis, & Newstead, 1988; Cushman, 1986; Gould et al., 1987; Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, & Luebker, 1987; Pastoor, 1990; A. H. Wang & Chen, 2000). For instance, Creed et al. (1988) investigated proofreading performance with positive and negative polarity text presentation. They reported that proofreading speed and accuracy were unaffected by display polarity. Furthermore, participants' preferences showed no significant differences regarding display polarity.

However, it is possible that the literature is less inconsistent than it seems to be. For instance, the null findings just mentioned might have been caused by low statistical power (e.g., Legge, Pelli, et al., 1985, with n = 6; Legge et al., 1987, with n = 2) or the use of flicker-prone cathode ray tube (CRT) monitors where distracting flicker is more apparent with positive than with negative polarity displays which may cancel out the normal positive polarity advantage (e.g., Creed et al., 1988; Cushman, 1986; Gould et al., 1987; Pastoor, 1990; A. H. Wang & Chen, 2000; for details, see Mayr & Buchner, 2010). Importantly, an advantage of negative polarity displays for normal-sighted observers has not been reported so far (although negative polarity displays might be advantageous in the case of severely vision-impaired observers; see Legge, Rubin, Pelli, & Schleske, 1985). All in all, positive polarity displays are expected to lead to better legibility than negative polarity text presentations for most observers. The size of the positive polarity advantage seems to be substantial. For example, Buchner and Baumgartner (2007) reported sample effect sizes of $\eta^2 = 0.23$, $\eta^2 = 0.06$, and $\eta^2 = 0.10$ in their experiments 1, 2, and 3, respectively. The mean of these sample effect sizes—that is, $\eta^2 = 0.13$—can be taken as a rough approximation to the population effect size. It corresponds to an effect of $f = 0.39$, which counts as a “large” effect in terms of the effect size conventions introduced by Cohen (1988).

A possible explanation for the positive polarity advantage is that the typically higher display luminance of positive polarity displays leads to a smaller pupil diameter which, in turn, is associated with a sharper retinal image and thus better perception of details[1]. For instance, in a recent study on display polarity with maximised contrasts the ambient illumination at the participants’ eye position was more than 30 times higher when participants proofread black-on-white (117 lx) as compared with white-on-black texts (3 lx) (Piepenbrock et al., 2013). It is assumed that the pupil constricts more strongly when focusing on a positive than a negative polarity display leading to a reduction in spherical aberrations (e.g., Liang & Williams, 1997; Lombardo & Lombardo, 2010; Y. Wang, Zhao, Jin, Niu, & Zuo, 2003). For instance, Xu, Bradley, and Thibos (2013) reported that the Zernike spherical aberration coefficient C_4^0 levels vary as the fourth power of pupil radius. For instance, 0.4 µm of spherical aberration for a 7 mm pupil diameter scales to $0.4(8/7)^4 = 0.6824$ µm for an 8 mm pupil diameter.

As a consequence, the depth of field increases, that is, the dioptric range for which the retinal image quality does not change noticeably becomes larger (e.g., Charman & Whitefoot, 1977; Green, Powers, & Banks, 1980). An increased depth of field will lead to an improved image quality if the eye is not perfectly focused. This is typically the case when performing near tasks, such as the reading of text. Here, participants commonly show a reduced accuracy of accommodation. The detrimental effects of this accommodative lag on visual acuity, however, are mitigated by pupillary constriction due to the concomitant increase in the depth of field (Lopez-Gil et al., 2013). Consequently, positive polarity displays should lead to an increased tolerance to accommodative errors for near targets and hence, higher text legibility.

Although the display luminance hypothesis emphasises that the pupil size plays an important role for the retinal image quality, this does not mean that a reduced pupil size unconditionally leads to a better perception of details. Whereas reduced spherical aberrations and an increased depth of field lead to a higher-quality projection on the retina (e.g., Berman et al., 1996), retinal image quality may suffer from very small pupil sizes due to the appearance of diffraction effects. For instance, Campbell and Gubisch (1966) reported an optimum pupil diameter of 2.4 mm that balances the trade-off between detrimental effects of diffraction and spherical aberrations.

Furthermore, it is possible that alternative mechanisms apart from the pupil constriction caused by the increase in display luminance underlie the positive polarity advantage in reading. One possible alternative hypothesis refers to the higher familiarity of positive polarity text presentations. Obviously, dark text on light background is ubiquitous in printed material. We may thus simply have more experience with reading from positive than from negative polarity displays, as a consequence of which the cognitive processes involved in reading may be particularly tuned to positive polarity displays (e.g., Hall & Hanna, 2004). Moreover, an asymmetrical resource allocation in the visual system starting in the retina and continuing up to V1 might play a role in explaining the positive polarity advantage (for a detailed elaboration on the magnitude of the black-white asymmetry in visual perception and its origin, see Lu & Sperling, 2012).

So far, the display luminance hypothesis of the positive polarity advantage has received some indirect support. For instance, the advantage of positive polarity vanishes when the overall display luminance is held constant between positive and negative polarity displays, suggesting that greater familiarity with positive than with negative polarity displays does not play a role (Buchner, Mayr, & Brandt, 2009). That same study showed that displays with overall greater brightness were associated with better performance. Further, with basic tasks such as simply gazing at single targets (Miyao et al., 1992) or successive gazing at a CRT display, a paper script, and a keyboard (Taptagaporn & Saito, 1990, 1993) pupillary constriction was stronger, and subjective preference was higher, for positive than for negative polarity displays. However, it is not known whether these findings can be generalised to normal sustained reading from displays.

The current study was conducted to test more directly the display luminance hypothesis of the positive polarity advantage in reading. Pupil size was measured while participants read texts from positive and negative polarity displays for spelling and grammatical errors. This proofreading task is an ecologically valid task that has been used in previous investigations of display polarity (Buchner & Baumgartner, 2007; Buchner et al., 2009; Piepenbrock et al., in press; Piepenbrock et al., 2013). Proofreading accuracy was measured in terms of the number of errors detected, corrected by the number of correct words falsely reported as incorrect. As a supplementary measure, the total number of words read was also assessed. Evidence in favour of the display luminance hypothesis would be a smaller average pupil size associated with better proofreading performance during reading from positive than from negative polarity displays. Given the rather moderate polarity-induced differences in ambient illumination in relation to the huge variations in daylight intensity to which the human visual system has to adapt, it is not clear whether variations in the relatively small amount of light emitted by the TFT monitor suffice to affect pupil size. Clearly, however, if pupillary constriction turns out not to be stronger with positive than with negative polarity displays, then the display luminance hypothesis is false and must be rejected.

2. Method

1.Participants

Participants were 35 volunteers (26 women) who were either paid or received course credits for participating. Eight additional participants had to be excluded from the analysis because their pupils could not be tracked in more than 5% of all recording samples, and one participant had to be excluded because the pupil size recording was interrupted during the experiment. Participants ranged in age from 20 to 30 years ($M = 24.31$, $SE = 0.47$). All participants were native German speakers. Normal or corrected-to-normal visual acuity was required (three participants wore hard contact lenses).

2.Material and task

The experiment took place in a dark room without any light sources other than the thin film transistor liquid-crystal display (TFT-LCD) and three table lamps that were placed in the corners of the room and were directed towards the wall. The ambient illumination at the participants' eye position was 0.1 lx (measured with a Gossen Mavolux 5032 B illuminance meter with Class B accuracy according to CIE no. 69) when the monitor was turned off. The text materials were presented on a 24-inch (1920 × 1200 pixels, 94.34 ppi) TFT-LCD of an Apple iMac computer (Apple Inc., CA, USA). In order to maximise contrast (as is recommended for digital text presentation, e.g. Nielson, 1999), the luminance of the white screen pixels was set to 328.8 cd/m^2, whereas the luminance of the black screen pixels was 0.6 cd/m^2. The text-background Michelson contrast was $c = (L_t - L_b)/(L_t + L_b) = (0.6\ \text{cd/m}^2 - 328.8\ \text{cd/m}^2)/(0.6\ \text{cd/m}^2 + 328.8\ \text{cd/m}^2) = -1.0$ in the positive polarity condition.

For the negative polarity condition, the contrast was $c = 1.0$. The ambient illumination at the participants' eye position was 118.4 lx in the positive polarity condition and 2.7 lx in the negative polarity condition. These illumination levels are rather low as compared with artificially illuminated office environments that are supposed to reach ambient illumination levels of at least 500 lx (European Standard, 2011). However, previous studies examined the effect of ambient illumination within a range of 5 lx to 800 lx, showing no significant effects of ambient illumination level on the positive polarity advantage (Buchner & Baumgartner, 2007) or on other aspects of visual performance (Lin & Huang, 2006; Menozzi, Napflin, & Krueger, 1999; Tseng, Chao, Feng, & Hwang, 2010; A. H. Wang, Tseng, & Jeng, 2007). A chin rest ensured a constant viewing distance of 50 cm.

In the proofreading task 36 texts of 250 words each were presented. Texts of the same polarity were presented in blocks of three. There were six positive and six negative polarity blocks presented in a random sequence. The texts were presented in 10 point Helvetica font (with x-height of 0.22° of visual angle), which is a common sans-serif font. Sub-pixel rendering was used for text presentation as has been implemented on Apple's Mac OS X. The maximal text width was 20.19 cm (22.83° of visual angle) and the texts covered 24 to 29 lines. The texts were presented single-spaced. A double-spaced text presentation could have facilitated reading due to a lower text density (e.g., Kruk & Muter, 1984; Lee, Ko, Shen, & Chao, 2011). However, Chan and Lee (2005) reported no significant interaction between line spacing and display polarity. Each text contained 14 errors of five different types. Errors comprised orthographic errors such as duplicate letters, missing letters, pair-wise letter inversions, and incorrect letters as well as grammar errors such as incorrect flexion or conjugation, which forced participants to read for comprehension rather than simply skim individual words. After having read all texts, participants completed a paper-based questionnaire regarding their subjective experiences during the proofreading task such as glare, reflections, text sharpness, and their ability to focus on the text (Table 1). During the experiment participants wore

SMI Eye Tracking Glasses (SMI SensoMotoric Instruments GmbH, Teltow, Germany), a non-invasive mobile video based glasses-type eye tracker that allows for binocular dark pupil tracking.

3.Procedure

Participants were tested individually. They were seated in front of the display. Participants were informed that their gaze behaviour and pupil size were recorded. First, a calibration was conducted during which three black to-be-fixated X's were presented subsequently on a white background on the display that was also used for the proofreading task. Afterwards, participants were instructed to find as many errors as possible in a series of short texts that they were asked to read silently. Participants were asked to read out loud all error-prone words they would encounter so as to ensure auditory recordings of high quality via the built-in microphone of the computer. Each text was presented for 50 s. The instructions emphasised accuracy rather than reading speed. Prior testing had confirmed that the texts were too long to be read completely within 50 s. After 25 s an auditive halftime cue was presented. After 50 s participants heard the auditory instruction to name the last two words that had been read.

The first text was a training passage containing the different types of errors. Performance was not evaluated for the training passage. The training could be repeated until the participants understood the task. Next, the experiment started and the 36 experimental texts were presented. Between two texts participants could take a break. They started the presentation of the next text at their own discretion. Between text blocks of different display polarity, the display luminance gradually changed within a transition period of 30 s. During the entire proofreading task, an experimenter was in the experimental room seated adjacent to the participant behind a movable wall. After the final text participants completed the questionnaire regarding their subjective experiences during the proofreading task. Overall, the session took about 45 mins.

4.Design

A within-subject design was used with display polarity (positive vs. negative) as the independent variable. The dependent variables were the proofreading accuracy calculated from the number of errors detected adjusted by the number of correct words falsely reported as incorrect (hits − false alarms) and the reading rate as measured by the amount of words read during the text presentation of 50 s. The central dependent variable was the pupil size (in mm) that was measured binocularly with a sampling rate of 30 Hz during the entire proofreading task.

Based on a pilot study, the polarity effect was expected to have an effect size of $d_z = 0.6$. In order to detect an effect of this size given desired levels of $\alpha = \beta = .05$, data had to be collected from a sample of at least $N = 32$ participants (Faul, Erdfelder, Lang, & Buchner, 2007). We were able to collect data from $N = 35$ participants. For the analysis of the pupil size data (with the SMI BeGaze^{TM} Eye Tracking Analysis Software, version 3.3 as of 2013-03-06, SMI SensoMotoric Instruments GmbH, Teltow, Germany) the recordings were cut into 36 segments, one for each text. Each segment covered the reading time excluding the first ten seconds resulting in 40 s length.

3. Results

1.Pupil size

Pupil size was significantly smaller in the positive than in the negative polarity condition, $t(34) = -17.49, p < .01, d_z = 2.96$ (Figure 1).

2.Proofreading performance

Proofreading accuracy (hits − false alarms) was significantly better in the positive than in the negative polarity condition, $t(34) = 4.54, p < .01, d_z = 0.77$ (Figure 1). In addition, reading rate (amount of words read) was significantly higher in the positive than in the negative polarity condition, $t(34) = 4.04, p < .01, d_z = 0.68$ (Figure 1).

To specify the contribution of the pupil size on participants' proofreading performance we used a linear mixed-effects model in which we entered the participants and texts as random variables assuming that they are independent and pupil size (in mm) as the continuous predictor of proofreading accuracy. The same model was used to predict reading rate. In this model, proofreading accuracy significantly increased with decreasing pupil size ($b = - 0.24$, $SE = 0.04$, $t = - 6.04$, $p < .01$). Similarly, reading rate significantly increased with decreasing pupil size ($b = - 2.12$, $SE = 0.41$, $t = - 5.12$, $p < .01$).

please insert Figure 1 about here

3.Subjective experiences

Table 1 shows the results of the post-task questionnaire. Participants were asked to compare the positive and negative polarity text presentations regarding several aspects of readability. Furthermore, they chose their overall display polarity preference. Participants' questionnaire responses were generally consistent with the positive polarity advantage.

please insert Table 1 about here

4. Discussion

Pupil size was significantly smaller when participants read positive polarity texts (2.09 mm) as compared with negative polarity texts (3.65 mm). This fits with the fact that the ambient illumination at the participants' eye position was higher in the positive (118.4 lx) than in the negative polarity condition (2.7 lx) of the proofreading task. Hence, normal variations in the amount of light emitted by the TFT monitor were enough to affect pupil size. This is astonishing considering the huge variations in daylight to which the human visual system has adapted with up to 150,000 lx on a sunny summer day. Also, proofreading accuracy was better and reading rate was higher when the text was presented in dark characters on light background compared to a presentation of light characters on dark background, that is, a typical positive polarity advantage. This finding is consistent with previous research that reported better legibility and higher visual comfort for positive polarity text presentations (e.g., Bauer & Cavonius, 1980; Buchner & Baumgartner, 2007; Chan & Lee, 2005; Mayr & Buchner, 2010; Piepenbrock et al., in press; Piepenbrock et al., 2013; Radl, 1980; Taptagaporn & Saito, 1990, 1993; Tsang et al., 2012). Furthermore, the positive polarity advantage was revealed in participants' subjective post-task-assessment. For example, a majority of participants reported an increased difficulty of focussing on individual words and of following the lines of text in the negative polarity condition. This fits well with other findings of better subjective evaluations of the visual comfort of positive as opposed to negative polarity displays (Saito, Taptagaporn, & Salvendy, 1993; Taptagaporn & Saito, 1990, 1993).

Taken together, these data are in line with the display luminance hypothesis according to which the positive polarity advantage is caused by the typically higher display luminance of positive polarity displays that results in a stronger pupil constriction, leading to a higher-quality projection on the retina and a better perception of small details. Pupil size was indeed smaller when reading positive polarity texts compared to a negative polarity text presentation. The important point here is that if the pupil size had not been smaller with positive than with negative polarity displays, then the display luminance hypothesis would have had to be rejected. Image quality was not measured directly in the present experiment because it has already been shown that smaller pupil sizes lead to sharper retinal images. For example, Campbell and Gubisch (1966) measured the reflected light of a bright line that served as the input stimulus in their study to infer the shape of the image on the retinal surface. They reported that the estimated linespread function for a pupil of a diameter of 3.0 mm was wider than the function for a 2.4 mm pupil indicating a sharper image for smaller pupil sizes. Note, however, that visual acuity may be limited by diffraction effects for pupil diameters smaller than 2.4 mm (Campbell & Gubisch, 1966). Considering that the mean pupil size in the positive polarity condition of the present experiment was 2.09 mm it is possible that the positive polarity advantage in performance would have been even larger for a somewhat darker positive polarity display which would have lead to a slightly larger pupil diameter.

However, given that we only measured but did not manipulate pupil size, the present experiment does not allow drawing conclusions about causal effects. In order to draw conclusions about a causal relationship between the pupil size and the positive polarity advantage an experimental manipulation of the pupil size would be needed. Strictly speaking, then, based on the current state of knowledge, the positive polarity advantage in proofreading performance cannot be unambiguously attributed to the smaller pupil sizes associated with positive polarity displays. Importantly, however, causal effects are not necessary for the critical test of the display luminance hypothesis reported here: If pupil size had stayed constant despite variations in display polarity, then the display luminance hypothesis would have had to be rejected. As mentioned above, one possibility is that the higher familiarity of dark text presented on light background contributed to the better proofreading performance for positive polarity text presentations (Hall & Hanna, 2004). Another variable that could play a role is that the retina devotes more resources to the processing of dark spots on light background than light spots on dark background (Ratliff, Borghuis, Kao, Sterling, & Balasubramanian, 2010). This asymmetry in the processing of light versus dark information by the visual system was also found in macaque V1 (Yeh, Xing, & Shapley, 2009) as well as in EEG and fMRI studies showing that human V1 responses to light decrements are stronger than to light increments (Zemon et al., 1988, 1995; Olman, Boyaci, Fang, & Doerschner, 2008). Although a predominance of processing resources for the coding of negative as compared with positive contrasts cannot explain why the positive polarity advantage vanishes when the overall display luminance of positive and negative polarity displays is equivalent (Buchner et al., 2009), this processing asymmetry might also contribute to the positive polarity advantage in reading text from TFT screens. Nevertheless it is clear that the establishing of a causal link between the pupil size and the positive polarity advantage would require an experimental manipulation of the pupil size.

A possible limiting factor for the ecological validity of the present findings is the low ambient illumination that was used. As mentioned before, several studies have reported no significant effects of ambient illumination on the positive polarity advantage in particular (Buchner & Baumgartner, 2007) and on visual performance in general (Lin & Huang, 2006; Menozzi et al., 1999; Tseng et al., 2010; A. H. Wang et al., 2007). The absence of an effect due to ambient illumination is most likely due to the improvement of anti-glare polarizer material in modern TFT monitors that leads to little reflected ambient illumination (Lin & Huang, 2006). However, illumination in these experiments was at about the level required for office work. It would be interesting to examine the effect of display polarity on pupil size and reading performance in the far more extreme situation of bright sunlight and under changing light conditions. Another possible limitation of the present study is that only young healthy adults were used as participants. As mentioned above, there is evidence indicating that the relation between polarity (and, hence, pupil size) and performance may be different for persons with low-vision (see for example Legge, Rubin, et al., 1985). Similarly, participants with a pathologically altered pupil light reflex might show a different performance pattern.

All in all, the display luminance hypothesis cannot be rejected, and is thus maintained, as a possible explanation of the positive polarity advantage. Thus, it cannot be ruled out that the positive polarity advantage is caused by the typically higher display luminance of positive polarity displays that results in a stronger pupil constriction, leading to a higher-quality projection on the retina and a better perception of small details. Thus, the data also emphasises the recommendation to present text in positive polarity.

Author Notes

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Footnotes

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[1] Different explanations for the function of the pupillary light reflex have been discussed, such as optimising visual resolution under differing lighting conditions, increasing sensitivity through the change in area of the pupil during dark adaptation, maintaining a constant retinal illumination, protecting the retina from dangerously bright lights, and preparing the eye in bright light for a subsequent return to the dark (Laughlin, 1992; Woodhouse, 1975; Woodhouse & Campbell, 1975).

Table 1

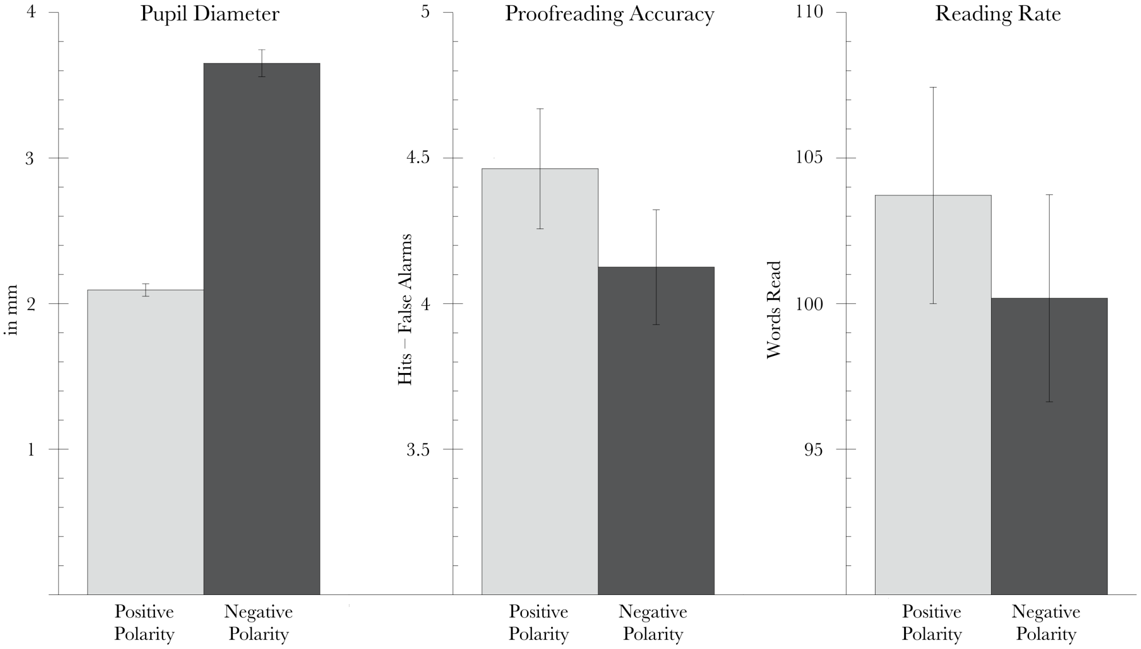
Results of the post-task questionnaire assessment of participants' subjective experiences

	Percentage			
Item	Positive Polarity	Negative Polarity	No Difference	*n*†
Difficulty of focussing on individual words was higher with ...	18	62	20	34
Difficulty of following the lines of text was higher with ...	9	55	36	33
Difficulty of jumping form one line of text to the next line was higher with ...	10	22	68	31
Amount of blur on the computer screen was higher with ...	17	77	68	30
Amount of glare on the computer screen was higher with ...	78	11	11	27
Amount of reflections on the computer screen was higher with ...	5	40	55	20
Overall preference	82	18	-	34

† *Sample sizes vary because some items were not assessed by all participants.*

Figure Captions

Figure 1: Mean pupil diameter (mm), mean proofreading accuracy (number of errors detected per text adjusted by false alarms), and mean reading rate (number of words read during 50 s) as a function of display polarity. The error bars represent the standard errors of the means.


Pupil Diameter
in mm
4
3
2
1
Proofreading Accuracy
Hits – False Alarms
5
4.5
4
3.5
Reading Rate
Words Read
110
105
100
95
Positive Polarity
Negative Polarity
Positive Polarity
Negative Polarity
Positive Polarity
Negative Polarity