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The advantage of positive text-background polarity is due to high display luminance

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Reading text from computer screens is better when text is printed in dark letters on light background (positive polarity) than when it is printed in light letters on dark background (negative polarity). An experiment is presented that tests whether this positive polarity advantage is due to the fact that overall display luminance is typically higher for positive than for negative polarity displays. To this end, text-background polarity and display luminance were manipulated independently. No positive polarity advantage was observed when overall display luminance of positive and negative polarity displays was equivalent. There was only an effect of display luminance, with better performance for the higher-luminance displays. This suggests that the positive polarity advantage is in fact due to the typically higher luminance of positive polarity displays. Readability of text presented on computer screens (e.g. on websites) is better when the overall display luminance level is high, as in positive polarity displays (dark letters on light background). Display polarity *per se* does not affect readability.

Keywords: display polarity; luminance; reading

Introduction

The presenting of dark letters on light background is usually referred to as negative contrast (because Michelson contrast $c = (L_t - L_b)/(L_t + L_b)$ turns negative if text luminance, L_t, is lower than background luminance, L_b) or positive text-background polarity. A number of studies have shown that presenting text on a monitor in positive polarity results in better performance than presenting text in negative polarity (Bauer and Cavonius 1980, Radl 1980, Magnussen et al. 1992, Wang et al. 2003, Chan and Lee 2005). However, there are also a number of failures to find such a positive polarity advantage (Cushman 1984, 1986, Legge et al. 1985, 1987, Gould et al. 1987, Creed et al. 1988, Pastoor 1990, Shieh 2000, Wang and Chen 2000, Ling and van Schaik 2002, Hall and Hanna 2004). Buchner and Baumgartner (2007) have suggested that these failures to find performance differences as a function of text-background polarity were mostly due to methodological problems. Specifically, they have shown that a reliable positive polarity advantage can be obtained provided that (a) an adequate sample size and (b) a between-subjects manipulation of text-background polarity is used. The latter reduces the chances of performance–effort trade-offs that complicate within-subject designs in which participants often try to maintain a certain performance level across difficult (here: negative text-background polarity) and easy (here: positive

text-background polarity) conditions by increasing or decreasing their effort, respectively.

The goal of the experiment reported here was to test hypotheses about the cause(s) of the positive polarity advantage. One important feature is that the overall luminance of positive polarity displays (e.g. black text on white background) is usually higher than that of negative polarity displays (e.g. white text on black background). For instance, overall display luminance in Experiment 1 of Buchner and Baumgartner (2007) was 180.30 cd/m^2 and 12.23 cd/m^2 in the positive and negative polarity condition, respectively. The luminance level of a viewed surface is an important determinant of pupil diameter. Pupil diameter, in turn, has effects on the depth of field and the magnitude of spherical aberrations. Indeed, Taptagaporn and Saito (1990) found that pupil diameter was smaller with positive than with negative polarity displays. This finding implies that there should be a greater depth of field and less spherical aberration and thus a higher quality of the retinal image with positive (high luminance level) than with negative (low luminance level) polarity displays. This, in turn, should be an advantage when reading text from positive polarity displays, as was noted by Taptagaporn and Saito (1990), although note that their participants did not read but simply looked at a monitor.

Another determinant of the positive polarity advantage could be that contrast sensitivity impairments due to adaptation processes while reading

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text from displays seem to be larger for negative than for positive polarity displays. Although this seems to be the case only for relatively low spatial frequencies (horizontal periodicity of rows) and not for more medium spatial frequencies corresponding to the vertical periodicity of characters (Magnussen *et al.* 1992), a smaller loss of contrast sensitivity for positive than for negative polarity displays could explain the positive polarity advantage.

A third variable that comes to mind is expertise as a function of familiarity. More precisely, the positive polarity advantage may simply be the result of one's extremely extended experience with positive text-background polarity in printed books, newspapers and magazines. It seems thus plausible to assume that brain areas involved in text processing may be tuned to the processing of positive polarity text displays.

The experiment reported herein focused on the role of display luminance for the positive polarity advantage. Specifically, it was tested whether the typically higher luminance level of a positive polarity text display may explain performance advantage over negative polarity displays. For that purpose, text-background polarity and display luminance were manipulated independently. First, a positive and a negative polarity condition were created so that in both conditions the overall display luminance was equally high and the absolute value of the text-background contrast was identical (although the sign of the contrast of course differed). Second, analogous positive and negative polarity display conditions with equally low overall luminance displays but with the same absolute value of text-background contrast as in the high luminance condition were created. If the positive polarity advantage were solely determined by the typically higher luminance of the positive polarity displays, then there should be (a) no difference between the positive and negative polarity display conditions and instead (b) better performance in the high than in the low display luminance condition. Alternatively, if the positive polarity advantage were (also) due to other variables such as contrast adaptation or familiarity, then a difference between positive and negative polarity displays should still be observed – perhaps, but not necessarily, in addition to a difference in performance between the high and low display luminance conditions.

Taptagaporn and Saito (1990) observed that the difference in pupil diameter between positive and negative polarity displays was larger with dark (20 lx) than with medium (500 lx) or bright (1200 lx) ambient illumination. However, the positive polarity advantage observed by Buchner and Baumgartner (2007) was unaffected by ambient illumination (5 lx vs. 550 lx). This suggests that if pupil diameter determines the positive polarity advantage in reading text from computer screens, then the absolute size of the pupil diameter difference is less important for, and not linearly related to, the positive polarity advantage, at least not as long as the ambient illumination is lower than or equal to 550 lx, the latter of which is in the order of magnitude of what is typically required for office environments (EN 12464–1, see e.g. DIN 2003). Given the independence of the polarity advantage of ambient luminance (at least in the range from 5 lx to 550 lx) it was decided to implement the experiment in the low ambient illumination condition used in the experiments of Buchner and Baumgartner. In order to maximise further the comparability of the present results to those earlier data, most other relevant features of the experiment (participants' task, equipment, materials (except for text and background luminance values) and procedure) were basically identical to the features of their experiments.

Method

Participants

Participants were 124 volunteers (81 women) who were paid for their participation. Their age ranged from 18 to 55 years (mean 26). All participants were tested individually. Participants were randomly assigned to the experimental groups with the restriction that, at the end of the experiment, an equal number of participants had to be in each of the four groups defined by the present 2×2 design. All participants had German as their native language and had normal or corrected-to-normal vision.

Apparatus and materials

The text materials were presented using an Apple 17-inch thin film transistor (TFT) 'Studio Display', which was controlled by an Apple PowerMacintosh computer (Apple Inc., CA, USA). A chin rest ensured a constant viewing distance of 50 cm. Luminance values were determined using a Minolta Colormeter CS-100 (Konica Minotta, Japan).

Overall display luminance was determined as follows. First, the average number of screen pixels that displayed text and background were determined for the 15 short stories that were used (6.11% of all screen pixels displayed text, 93.89% displayed background). Next, the display luminance as a function of RGB values was determined. To this end, RGB values were incremented from (15, 15, 15) to (255, 255, 255) in steps of 15, simultaneously for each colour channel. Luminance was recorded for each level. A power function was fitted to these observed data to predict the displays' luminance from arbitrary RGB values (fit: $R^2 > 0.99$). For the positive polarity condition (dark

text on light background), text and background luminance were determined such that the text-background Michelson contrast was $c = (L_t - L_b)/(L_t + L_b) = -0.30$. For the negative polarity condition (light text on dark background), the contrast was $c = 0.30$. Within each level of the polarity variable, the text and background display luminance values were determined such that the overall display luminance difference between the high and low display luminance condition was maximised given the capabilities of the TFT display that was used, the contrast that was implemented and the need to avoid very extreme RGB settings. The resulting overall display luminance values were 77 cd/m^2 and 10 cd/m^2 in the high and low display luminance conditions, respectively. The corresponding text and background luminance values are displayed in Table 1.

Participants performed the spell-checking task (see Procedure) in a dark, soundproof room without windows. Ambient illumination was 5 lx when the RGB values of the computer screen were set to (0, 0, 0). Participants read 15 separate short stories by various authors. Each story was 875 words long and was presented in 14 point Helvetica (letter height was 0.4° of visual angle) in which it filled one page on the computer screen (between 35 and 40 lines of text). Each story contained 30 errors of five different types (duplicate letters, missing letters, pair-wise letter inversions, incorrect letters and grammar errors such as incorrect flexion or conjugation, which forced participants to comprehend the text rather than simply skim individual words). To anticipate the results, none of the results differed systematically as a function of the type of spelling error, which is why only the overall number of detected errors is reported.

Procedure

After the participants were comfortably seated and properly positioned, they were instructed that their task in this experiment was to find as many errors of various types in a series of short stories that they would be asked to read. They received a training passage of text containing the different types of errors. Participants learned that they were to mark errors by double-clicking the relevant word using the computer mouse. As soon as they clicked on a word, a small 'record' and a 'cancel' button appeared to the right of the text passage. If participants were certain to have selected a spelling error, they were to click on the 'record' button, after which the selected word was recorded for later evaluation. The word was then de-selected and the buttons disappeared immediately. Otherwise, participants could de-select the word by clicking the 'cancel' button, in which case the buttons disappeared immediately. It was not possible to select more than one word at a time. This training interval lasted about 10 to 15 min and also served as the dark adaptation interval.

Next, every participant received a random sequence of 15 short stories. Every short story was presented for 3 min, during which participants had to select as many errors as they could. Prior testing as well as the experience gained in Buchner and Baumgartner's (2007) experiments had confirmed that the stories were too long to be read completely within 3 min. After the 3-min period errors could no longer be detected and a male voice announced that the next short story was about to be presented, which indeed occurred 3 s later.

During the entire experiment, an experimenter was in the experimental room, seated behind the participant, to survey the task progress and to aid the participant should she or he decide to quit the experiment ahead of time (this did not occur). Overall, the experiment took about 1 h.

Design

The between-subjects independent variables in the present $2 \times 2 \times 15$ design were text-background polarity (dark-on-light ($c = -0.30$) vs. light-on-dark ($c = 0.30$)) and display luminance (high (77 cd/m^2) vs. low (10 cd/m^2)). The within-subject independent variable was story number (story 1 to story 15). The dependent variable was the number of spelling errors detected.

The sample effect sizes of the polarity effect observed in Buchner and Baumgartner (2007) were $\eta^2 = 0.23$ ($f = 0.55$), $\eta^2 = 0.06$ ($f = 0.25$), and $\eta^2 = 0.10$ ($f = 0.33$) in their Experiments 1, 2 and 3, respectively. With an average of $\eta^2 = 0.13$ ($f = 0.39$), the polarity effect may count as 'large' in terms of the conventions introduced by Cohen (1977). Based on this size and the observed range of effect sizes it was thought reasonable to aim at detecting a polarity effect even if it were somewhat smaller than what had been previously observed, that is, an effect of $\eta^2 = 0.10$

Table 1. Luminance values (cd/m^2) of text and background as a function of text-background polarity (positive, negative) and display luminance (high, low).

Display luminance	Positive polarity		Negative polarity	
	Text	Background	Text	Background
High (77 cd/m^2)	42.67	79.24	135.88	73.17
Low (10 cd/m^2)	5.54	10.29	17.65	9.50

Note: The overall display luminance is presented in parentheses. It was calculated as the weighted average of the luminance of screen pixels displaying text (6.11%) and background (93.89%).

($f = 0.33$) was planned for. Given this, an a priori power analysis suggested that for desired levels of $\alpha = \beta = 0.05$, data would have to be collected from $n = 124$ participants, 31 in each of the cells of the present 2×2 between-subjects part of the design (Faul *et al.* 2007, Mayr *et al.* 2007).

Results

Figure 1 shows that performance was very similar in the positive and in the negative polarity condition, but that display luminance had an effect on the number of errors that were detected. A $2 \times 2 \times 15$ multivariate ANOVA with text-background polarity and display luminance as between-subjects independent variables and story number (story 1 to story 15) as within-subject variable showed no effect of text-background polarity, $F(1, 120) = 0.04$, $p = 0.85$, $\eta^2 < 0.01$, but a significant effect of display luminance, $F(1, 120) = 16.18$, $p < 0.01$, $\eta^2 = 0.12$. The interaction between these variables was not significant, $F(1,120) = 0.28$, $p = 0.59$, $\eta^2 < 0.01$, and neither was any of the interactions with the story number variable, all $F(14, 107) < 1.14$, $p > 0.33$, $\eta^2 < 0.13$. At a descriptive level, performance seemed to improve as a function of the number of stories that were read, but the effect of this variable just missed the preset level of statistical significance, $F(14, 107) = 1.76$, $p = 0.06$, $\eta^2 = 0.12$.

Discussion

Proofreading performance was clearly superior in the high relative to the low display luminance condition. The size of the display luminance effect in the present
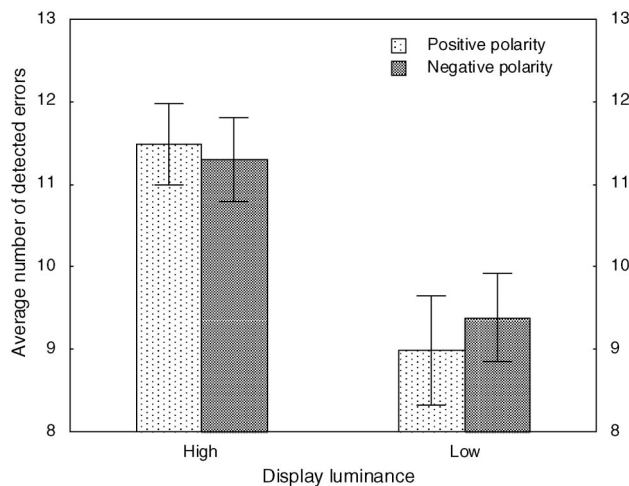

Figure 1.   Mean number of errors detected in the each of the 15 stories (30 at most) as a function of polarity and display luminance. The error bars represent the standard errors of the means.

experiment ($\eta^2 = 0.12$ or $f = 0.37$) was rather close in magnitude to the average polarity effect observed by Buchner and Baumgartner (2007) ($\eta^2 = 0.13$ or $f = 0.39$). The absolute performance level was also strikingly parallel. In the present high display luminance conditions and in Buchner and Baumgartner's positive polarity conditions the numbers of detected errors were 11.4 and 11.9, respectively. In the present low display luminance conditions and in Buchner and Baumgartner's negative polarity conditions the numbers of detected errors were 9.2 and 9.5, respectively. Recall that in the experiments reported by Buchner and Baumgartner, text-background polarity implied the usual confounding with display luminance in that overall display luminance was high for positive (between 177.87 cd/m² and 180.30 cd/m²) and low for negative polarity displays (between 12.23 cd/m² and 32.42 cd/m²). Thus, those earlier and the present data can be summarised by stating that proofreading performance in all of these experiments was better when display luminance was high than when it was low. This is parallel to other studies in which screen luminance was manipulated directly (e.g. Lin 2005). At the same time, there was no polarity effect in the present experiment, that is, there was no longer a positive polarity advantage when the overall display luminance did not differ between positive and negative polarity displays. All of these effects were independent of the number of stories read, that is, practice effects did not modulate any of these effects.

Taken together, this suggests that the polarity effect is in fact an effect of display luminance. In other words, the positive polarity advantage in reading text from computer displays is due to the fact that displays with dark letters on light background are typically brighter than negative polarity displays with light letters on dark background. Other variables, such as contrast adaptation or familiarity seem to be of very little or no relevance for the polarity effect.

A factor that may limit the generality of the present results is that the ambient illumination in the present experiment was low (5 lx). However, given that the polarity effect reported by Buchner and Baumgartner (2007) did not differ as a function of whether the ambient illumination was 5 lx or 550 lx, it seems safe to conclude that the present results can be generalised at least to the ambient illuminations up to 550 lx, which is a level that is typical for artificially illuminated office environments. In addition, other studies have also found that, when using TFT monitors, visual performance is not affected by ambient illumination varying between 200 lx and 800 lx (Lin and Huang 2006, Wang *et al.* 2007). This is probably so because modern TFT monitors reflect only a small proportion

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of the ambient light so that the text-background contrast is only marginally affected by relatively low-intensity external light sources. In contrast, ambient illumination varying between 300 lx and 1500 lx appears to affect reading from electronic paper displays, which is to be expected because these displays are reflective (Lee *et al.* 2008). Finally, even reading from low-reflective TFT displays may become a problem with very high-intensity light sources such as the sun outdoors (Chung and Lu 2003).

Within these limits the current data suggest that the positive polarity advantage in reading text from computer displays is in fact a high display luminance advantage, possibly mediated by a smaller pupil size compared to that associated with low display luminance of negative polarity displays.

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