Displays and Controls

Positive display polarity is particularly advantageous for small character sizes - Implications for display design

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Running head: Polarity & Character Size

word count (text): 4476 (4588 incl. author notes & list of key points)

word count (references): 1253

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ABSTRACT

Objective: To test the display luminance hypothesis of the positive polarity advantage and gain insights for display design the joint effects of display polarity and character size were assessed using a proofreading task.

Background: Studies have shown that dark characters on light background (positive polarity) lead to better legibility than light characters on dark background (negative polarity), presumably due to the typically higher display luminance of positive polarity presentations.

Methods: Participants performed a proof-reading task with black text on white background or white text on black background. Texts were presented in four different character sizes (8, 10, 12, and 14 pt; corresponding to 0.22°, 0.25°, 0.31°, and 0.34° of vertical visual angle).

Results: A positive polarity advantage was observed in proofreading performance. Importantly, the positive polarity advantage linearly increased with decreasing character size.

Conclusion: The findings are in line with the assumption that the typically higher luminance of positive polarity displays leads to an improved perception of detail.

Application: The implications seem important for the design of text on displays such as those of computers, automotive control and entertainment systems, or smartphones that are increasingly used for the consumption of text-based media and communication. The sizes of these displays is limited, and it is tempting to use small font sizes in order to convey as much information as possible. Especially with small font sizes, negative polarity displays should be avoided.

KEYWORDS

display polarity, contrast polarity, positive polarity advantage, character size, font size, mobile devices, smartphones, text-based communication, detail perception, display design

PRÉCIS

Dark characters on light background (positive polarity) lead to better legibility than light characters on dark background (negative polarity). This advantage linearly increases with decreasing character size. Positive polarity text presentation is recommended, particularly for small characters.

Positive display polarity is particularly advantageous for small character sizes - Implications for display design

INTRODUCTION

Ergonomic display design depends on various factors, such as whether text is displayed using dark characters on light background (positive polarity) or light characters on dark background (negative polarity). Several authors reported better legibility of a positive as compared with a negative display polarity. For instance, a positive polarity advantage was demonstrated in terms of lower error rates and response times in letter identification (Bauer & Cavonius, 1980), faster transcription of displayed letters (Radl, 1980), faster reading performance (Chan & Lee, 2005), better proofreading performance (Buchner & Baumgartner, 2007; Piepenbrock, Mayr, Mund, & Buchner, in press), better word-nonword discrimination (Mayr & Buchner, 2010), increased visual acuity (Piepenbrock et al., in press), and higher visual comfort (Taptagaporn & Saito, 1990, 1993). Findings of no positive polarity advantage have also been reported. For instance, no differences between positive and negative polarity displays have been reported for reading speed and comprehension (Cushman, 1986), proofreading rate and accuracy (Creed, Dennis, & Newstead, 1988; Gould et al., 1987), reading rate (Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, & Luebker, 1987), reading time, search time, and subjective preference (Pastoor, 1990), as well as visual acuity and perceived display quality (A. H. Wang & Chen, 2000). However, these findings may have been the result of low statistical power (e.g., Legge et al., 1985, with n = 6; Legge et al., 1987, with n = 2) and the use of flicker-prone cathode ray tube (CRT) monitors (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). A negative polarity advantage does not seem to have been reported to date for observers with normal vision, so that the overall pattern of results suggests that the positive polarity advantage can be considered as real.

There are several explanations of the positive polarity advantage. Texts presented in positive polarity (which is typical of printed materials) is much more familiar than negative polarity text such that the cognitive processes involved in reading might perhaps be particularly tuned to the recognition of dark letters on light background. Furthermore, dark text on light background is usually associated with a higher overall display luminance than light text on dark background. Accordingly, focussing on a positive polarity text presentation results in a stronger contraction of the pupil than focussing on a negative polarity display (e.g., Miyao et al., 1992; Taptagaporn & Saito, 1990, 1993; but see Zwahlen & Kothari, 1986). The greater pupillary contraction reduces the effects of spherical aberrations due to the smaller pupil diameter (e.g., Liang & Williams, 1997; Lombardo & Lombardo, 2010; Y. Wang, Zhao, Jin, Niu, & Zuo, 2003). In fact, spherical aberration increases by the fourth power of pupil diameter. Consequently, reducing pupil diameter by half leads to a 16-fold decrease in spherical aberration (American Academy of Ophthalmology, 2009). Also, the depth of field increases (e.g., Charman & Whitefoot, 1977; Green, Powers, & Banks, 1980). As a result, the retinal image becomes sharper, leading to higher visual acuity and better perception of fine details (e.g., Berman et al., 1996). Note that this inverse relation between pupil diameter and retinal image quality holds with the exception of very small pupil sizes where diffraction effects might limit image quality (Campbell & Gubisch, 1966). This means that the positive polarity advantage might turn into a disadvantage above a certain luminance level at which the light scatter induced by diffraction would begin to impede the perception of fine details such as small characters.

Some empirical support for display luminance as the main explanatory factor of the positive polarity advantage comes from Buchner, Mayr, and Brandt (2009) who manipulated text-background polarity and display luminance independently. They used a 2×2 design with text-background polarity and display luminance (calculated as the weighted average of the luminance of screen pixels displaying text and background) as independent variables and equal contrast in all four conditions. No advantage of positive polarity was observed when the overall display luminance was held constant between positive and negative polarity displays. Instead, the crucial factor was the display luminance, with better performance for the higher-luminance displays. However, it seemed desirable to provide an independent test of the display luminance hypothesis of the positive polarity advantage. If the typically higher overall display luminance of positive polarity displays indeed facilitates the perception of fine details, then the positive polarity advantage in reading should become larger as a function of decreasing character size. This prediction was tested in the study presented here. The prediction capitalizes on the fact that legibility has been found to decrease with decreasing character size (e.g., Bernard, Chaparro, Mills, & Halcomb, 2003; Fagan, Westgate, & Yolton, 1986; Griffing & Franz, 1896; Luckiesh & Moss, 1939; Miyao, Hacisalihzade, Allen, & Stark, 1989), presumably because, for very small characters, legibility is limited by visual acuity (S. L. Smith, 1979). Given this, the legibility of text should suffer further when visual acuity is reduced due to the use of a negative polarity display.

However, a factor that could impinge upon this predicted relationship between display polarity and character size is the so called irradiation effect, that is, the apparent enlargement of a bright object seen against a dark background as compared with a dark object of equal size against a bright background. An explanation of this optical illusion is that light from the bright area spreads beyond the edges into the dark side of the border (Westheimer, 2007). For instance, Kong, Kim, Lim, Han, and Jung (2011) reported that white letters on a black background were perceived as being larger than black letters on a white background. It is an empirical question whether such an increase in subjectively perceived character size is associated with objectively better legibility of negative polarity characters. If so, small characters that are difficult to identify should benefit more from the enlargement due to irradiation than large, easy-to-read characters. Hence, according to the irradiation hypothesis, the positive polarity advantage should be reduced or even neutralized for small as compared with large character sizes.

From an applied point of view the legibility of small characters is an important concern whenever text has to be presented within limited space. Also, given the considerations explicated in the previous paragraph, the legibility of small characters may be even more of a concern when text and background color can be easily manipulated, such as with computer displays or displays of automotive control and entertainment systems for which the display of black or colored text backgrounds does not come at an additional cost of production, which is different for print media. Compared to a newspaper page, for instance, the size of the modal computer screen seems quite limited, such that designers of internet-based news media may feel tempted to use small font sizes in an attempt to maximize what can be displayed simultaneously on the readers' displays. Screen space is even more limited on smartphones that are increasingly used for text-based media consumption (A. Smith, 2011) and for text-based communication (Office of Communications, 2012). With display diagonals in smartphones of 4 to 5 inches (and of only between 1 to 2 inches in smartwatches), ensuring the readability of small characters becomes even more of a challenge for display designers. According to Legge and Bigelow (2011) normally sighted people can achieve fluent reading when text is composed of characters with x-heights ranging from 0.2° to 2° of visual angle. Bababekova, Rosenfield, Hue, and Huang (2011) measured the character sizes of their participants' personal smartphones when viewing text messages or web pages. The mean character x-height was 0.27° of visual angle (ranging from 0.12° to 0.49°) when viewing text messages. The character sizes were even smaller when viewing web pages (mean x-height was 0.21°, ranging from 0.08° to 0.40°). The mean text sizes are at the lower end of what Legge and Bigelow determined to be necessary for fluent reading, and the lower sections of the text size distributions are clearly below the lowest fluent reading limit, illustrating the need to optimize other variables affecting text legibility, such as display polarity.

In the present study, the joint effects of display polarity and character size were assessed using a proofreading task. Texts were presented either in positive (black text on white background) or negative polarity (white text on black background) at four different character sizes (8 pt, 10 pt, 12 pt, and 14 pt; corresponding to 0.22°, 0.25°, 0.31°, and 0.34° of visual angle given a viewing distance of 50 cm). An effect of display polarity, an effect of character size, and an interaction between both variables was expected such that the positive polarity advantage should be larger when reading text written in small as compared to large character size. Note that this interaction is predicted by the display luminance hypothesis of the positive polarity advantage according to which the typically higher overall display luminance of positive polarity displays facilitates the perception of fine details. The opposite result would be expected based on the irradiation hypothesis according to which the positive polarity advantage should become smaller with decreasing character size because small characters should benefit more than large characters from the subjective enlargement of the letter size. Similarly, if the pupil sizes in the present experiment were so small that diffraction came into play, then the positive polarity advantage should be reduced for smaller character sizes. Finally, if other factors such as familiarity were mainly responsible for the advantage of dark text on light background, then the greater legibility for positive polarity displays should be independent of character size, that is, there should be no interaction between display polarity and character size.

METHOD

Participants

Participants were 165 volunteers (119 women) who received partial course credit or a monetary compensation for participating. Data from five participants were excluded from the analysis because an analysis of the protocols revealed that they had read only the first few and the last few sentences of the texts (see below), skipping most of the text. The remaining participants ranged in age from 18 to 44 years (M = 23.6, SE = 0.3). They were randomly assigned to the positive and negative polarity conditions with the restriction that, at the end of the experiment, a comparable number of participants had to be in each group. All participants were native German speakers and reported normal or corrected-to-normal visual acuity.

Material and task

The experiment took place in a dark room without light sources other than the display used for the proofreading task and three table lamps that were placed in the corners of the room and directed towards the wall. The ambient illumination at the participant's eye position was < 0.1 lx (measured with a Gossen Mavolux 5032 B illuminance meter with an optional luminance attachment with Class B accuracy according to DIN 5032-7) when the monitor was turned off. The texts for the proofreading task were presented on a 24-inch (1920 × 1200 pixels, 94.34 ppi) thin film transistor (TFT) display of an Apple iMac computer. In order to maximize contrast, the luminance of white screen elements was set to 342 cd/m^2 (RGB values of [255, 255, 255]), whereas the luminance of black screen elements equalled 1 cd/m^2 (RGB values of [0, 0, 0]). The text-background Michelson contrast was $c = (L_t - L_b)/(L_t + L_b) = -1$ in the positive polarity condition (black text on white background). In the negative polarity condition (white text on black background), the contrast was $c = 1$. The ambient illumination at the participants' eye position equalled 116 lx in the positive polarity condition and 4 lx in the negative polarity condition. A chin rest ensured a constant viewing distance of 50 cm.

During the proofreading task participants read 40 texts of 250 words each. Sub-pixel rendering was used for text presentation as implemented in Apple's Mac OS X. For each participant, ten of the 40 texts were randomly assigned to one of the four character size conditions: 8 pt Helvetica (with x-height of 0.22° of visual angle), 10 pt Helvetica (0.25°), 12 pt Helvetica (0.31°), and 14 pt Helvetica (0.34°). Text width varied with character size from 17 cm to 30 cm, corresponding to visual angles of 19° and 33° at a reading distance of 50 cm. Gould and Grischkowsky (1986) reported that proofreading speed and accuracy were unaffected by line widths ranging from of 16° to 36° of visual angle. The variation in text width allowed for comparable numbers of words per line and for comparable numbers of lines (14 to 16 lines) in all character size conditions. Each text contained 14 errors of five different types. Errors comprised orthographic errors such as duplicate letters, missing letters, pairwise letter inversions, incorrect letters, and grammar errors such as incorrect flexions or conjugations, which forced participants to read for comprehension rather than simply skim individual words. After having read all 40 texts, the participants completed a paper-based questionnaire assessing their subjective experiences during the proofreading task. They rated aspects such as glare, reflections, text sharpness, and their ability to focus on the text.

Procedure

Participants were tested individually. The written experimental instructions and the texts of the proofreading task were presented on the same display and using the same polarity. Participants were seated in front of the display at a reading distance of 50 cm. They were instructed to find as many errors as possible in a series of short texts that they were asked to read silently. They received a training text containing the different types of errors. Participants were asked to read out loud all words identified as erroneous. These responses were recorded using the computer's built-in microphone. Texts were presented for 50 s. The instructions emphasized 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 auditory halftime cue was presented. After 50 s participants received the auditory instruction to name the last two words that they had read. The training could be repeated until the participants understood the task. Next, every participant received a random sequence of 40 texts which were to be read given the same conditions as for the training text. Between two texts participants could take a break. They started the presentation of the next text at their own discretion. During the entire proofreading task, an experimenter was in the experimental room, seated behind the participant. After the final text participants completed a post-task questionnaire assessing their subjective experiences during the proofreading task (see Table 1). Overall, the experiment took about 45 mins.

Design

For each character size, the first text was excluded from the analysis in order to prevent possible effects of irritation caused by the new character size from contaminating the results. Thus, 36 texts, nine in each level of the character size variable, were used for analysis. A 2×4×9 mixed design was used with display polarity (positive vs. negative) as a between-subjects variable and character size (8 pt, 10 pt, 12 pt, 14 pt) as well as trial (1-9) as within-subject variables. The dependent variables were proofreading performance derived from the number of errors detected adjusted by the false alarms (in analogy to P_r = hit rate − false alarm rate) and reading rate as measured by the number of words read.

The level of alpha was set to .05, and alpha and beta errors were considered equally serious. Given levels of $\alpha = \beta = .05$, an assumed population correlation of $\rho = .30$ among the levels of the character size repeated measures variable, and the goal to detect a "small" to "medium" interaction effect of size $f = 0.15$ (as defined by Cohen, 1988) between display polarity and character size, data had to be collected from a sample of at least $N = 136$ participants (Faul, Erdfelder, Lang, & Buchner, 2007). We collected data from $N = 160$ participants (78 in the positive and 82 in the negative polarity condition) so that the effect that could be detected was even slightly smaller than what we had planned for ($f = .14$). *P*-values smaller than .10 are reported to three decimal places for added clarity.

RESULTS

Proofreading performance

The left panel of Figure 1 shows that performance was better in the positive than in the negative polarity condition for all character sizes and that more errors were detected with increasing character size. The right panel of Figure 1 shows that the positive polarity advantage increased with decreasing character size. A 2×4×9 MANOVA with polarity as between-subjects variable and character size and trial as within-subject variables showed statistically significant effects of polarity, $F(1, 158) = 9.34$, $p = .003$, $\eta^2 = .056$, and character size, $F(3, 156) = 83.66$, $p < .001$, $\eta^2 = .62$. The interaction between these variables was also statistically significant, $F(3, 156) = 3.16$, $p = .026$, $\eta^2 = .057$. Specifically, there was a significant interaction between polarity and the linear trend component of the character size variable, $F(1, 158)$

= 8.92, p = .003, η^2 = .053, indicating that the positive polarity advantage increased linearly with decreasing character size. The interaction of polarity with the quadratic and cubic components of the character size variable were not significant, both $Fs < 1$. Neither the main effect of trial nor any other interaction effect was statistically significant, all $Fs < 1.43$, $p > .17$, $\eta^2 < .19$.

please insert Figure 1 about here

Reading rate

The left panel of Figure 2 shows that reading was faster in the positive than in the negative polarity condition for all character sizes and that more words were read with increasing character size. The right panel of Figure 2 shows that the positive polarity advantage increased with decreasing character size. In the 2×4×9 MANOVA with polarity as between-subjects variable and character size and trial as within-subject variables the effect of polarity just missed the preset level of significance, $F(1, 158) = 2.60$, $p = .055$, $\eta^2 = .016$. The effect of character size, $F(3, 156) = 15.86$, $p < .001$, $\eta^2 = .23$, and the interaction between polarity and character size were statistically significant, $F(3, 156) = 4.70$, $p = .004$, $\eta^2 = .083$. Specifically, there was a significant interaction between polarity and the linear trend component of the character size variable, $F(1, 158) = 10.61$, $p = .001$, $\eta^2 = .063$, indicating that the positive polarity advantage increased linearly with decreasing character size. The interaction of polarity with the quadratic and cubic components of the character size variable were not significant, both $Fs < 1$. Moreover, the effect of trial was significant, $F(8, 151) = 2.98$, $p = .004$, $\eta^2 = .14$, with a decreasing number of words read with progressing testing. All other interactions were not statistically significant, all $Fs < 1.31$, $p > .24$, $\eta^2 < .17$.

please insert Figure 2 about here

Questionnaire data

In the post-task questionnaire (Table 1), participants reported no significant difference between the positive and negative polarity displays in aspects of text readability (such as the ability to focus on text) which is interesting given the clear positive polarity advantage in the objective performance measures. Participants reported a higher amount of blur on the computer screen as well as a higher difficulty of jumping from one line of text to the next line in the negative as compared with the positive polarity condition. By contrast, participants reported a higher amount of glare in the positive as compared with the negative polarity condition.

Table 1

Results of the post-task questionnaire assessment of participants' subjective experiences on a scale from 1 (no difficulty; no blur, glare, or reflections) to 4 (considerable difficulty; considerable blur, glare, or reflections)

	Mean rating					
Item	Positive Polarity	Negative Polarity	*t*	*df*†	*p*	*d*
Difficulty of focussing on individual words	2.00	2.06	- 0.61	156	.27	- 0.10
Difficulty of following the lines of text	1.73	1.70	0.21	156	.42	0.043
Difficulty of jumping form one line of text to the next line	1.47	1.65	- 1.68	154	.048	- 0.25
Amount of blur on the computer screen	1.44	2.08	- 5.31	155	< .001	- 0.74
Amount of glare on the computer screen	1.97	1.68	2.00	157	.024	0.32
Amount of reflections on the computer screen	1.30	1.24	0.62	154	.27	0.11

† Degrees of freedom vary due to data loss.

DISCUSSION

The results of the present study show a typical positive polarity advantage in terms of better proofreading performance for text presented in dark characters on light background (positive polarity) than for text presented in light characters on dark background (negative polarity). This finding is in line with previous research (e.g., Bauer & Cavonius, 1980; Buchner & Baumgartner, 2007; Chan & Lee, 2005; Mayr & Buchner, 2010; Piepenbrock et al., in press; Taptagaporn & Saito, 1990, 1993). The same is true for the finding that larger character sizes improved text legibility leading to better proofreading performance and higher reading speed (cf., Bernard et al., 2003; Fagan et al., 1986; Griffing & Franz, 1896; Luckiesh & Moss, 1939; Miyao et al., 1989; S. L. Smith, 1979).

The important new finding is that the positive polarity advantage linearly increased with decreasing character size. This finding is predicted by the display luminance hypothesis of the positive polarity advantage (Buchner et al., 2009). According to this hypothesis, the typically higher overall display luminance of positive polarity displays leads to a stronger contraction of the pupil which reduces spherical aberrations and increases the depth of field (e.g., Charman & Whitefoot, 1977; Green et al., 1980; Liang & Williams, 1997; Lombardo & Lombardo, 2010; Y. Wang et al., 2003), thereby facilitating the perception of fine details. The perception of small details should be more important for small characters (S. L. Smith, 1979). This is what we observed. The present data are inconsistent with the irradiation hypothesis according to which the positive polarity advantage should have been smaller for small characters which should have benefitted more from the subjective enlargement than large letters. Similarly, diffraction effects do not seem to have played a role in the present experiment. However, diffraction effect are known to occur only at very small pupil sizes (Campbell & Gubisch, 1966) which may not have occurred in the present experiment. Finally, the present data are inconsistent with the assumption that variables such as familiarity were mainly responsible for the advantage of dark text on light background. If this were the case, then a positive polarity advantage would have been expected to be independent of character size.

The practical implications of the present study are obvious. First, the present data strengthen the general recommendation to present text in positive polarity. This recommendation seems particularly important when small character sizes are used. We know that on smartphones text is typically presented using small characters, with x-heights averaging around 0.21° to 0.27°, but extending as low as 0.08° (Bababekova et al., 2011). These average character sizes approximate the two smallest character sizes displayed in the present study (0.22° and 0.25°). Thus, the present results speak directly to the to-be-preferred polarity for presenting text on these small-screen devices. However, screen size is quite limited in other devices as well. For instance, automotive control and entertainment systems which also display text are becoming more common, both in addition to, but also replacing, traditional analog dashboard instruments. Given that these devices will often be used during driving, it is obvious that reading should be facilitated as much as possible. Thus, positive polarity displays seem to be an obvious choice here, too. Unfortunately, things are not so simple. For instance, positive polarity displays emit more light than negative polarity displays. When driving at night, light emitted by displays in a car reduces the dark adaptation of the driver's eyes, thereby reducing the driver's sensitivity to low-contrast objects on, or on their way to, the road. Positive polarity displays should therefore lead to a larger sensitivity reduction for such objects than negative polarity displays, and this is in fact the case (Mayr & Buchner, 2010). A possible solution may be to use red instead of white as the background color because the cones in the human retina are mostly insensitive to the red light emitted by typical TFT-LCD displays. However, this is beyond the scope of the present article.

Another interesting observation is that participants' subjective assessments of aspects of text readability (such as the ability to focus on text; Table 1) showed no difference between positive and negative polarity, although their objective performance was clearly better with positive than with negative polarity displays. This may indicate that users are insensitive to the effects of display ergonomics on their performance. It is thus up to the designers to take the advantage of positive polarity displays into account.

A possible limiting factor for the ecological validity of the present study is the low ambient illumination of the experimental setting. This concern is reduced to some degree by previous studies that have shown that the effects of ambient illumination on the positive polarity advantage (Buchner & Baumgartner, 2007) and on visual performance in general (Lin & Huang, 2006; A. H. Wang, Tseng, & Jeng, 2007) are negligible within the range of 5 lx to 800 lx. Still, from an application-oriented point of view, it would be interesting to investigate how bright sunlight illumination or altering light conditions impact the positive polarity advantage. Currently, this is an open question.

In sum, the present study confirms the assumption that the positive polarity advantage in reading texts from displays is mostly due to the typically higher display luminance of positive polarity presentations. The present data also underscore the validity of the general recommendation to present text in positive polarity, particularly when small character sizes are used that pose strong demands on visual acuity.

AUTHOR NOTES

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KEY POINTS

- Dark characters on light background (positive polarity) lead to better proofreading performance than light characters on dark background (negative polarity).
- The positive polarity advantage linearly increased with decreasing character size suggesting that the typically higher luminance of positive polarity displays leads to an improved perception of detail.
- Dark characters on light background are recommended because they lead to better legibility than light letters on dark background, particularly for small characters.

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