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# Positive display polarity is advantageous for both younger and older adults

Cosima Piepenbrock*, Susanne Mayr, Iris Mund and Axel Buchner

*Institut für Experimentelle Psychologie, Heinrich-Heine-Universität, Düsseldorf, Germany*

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The effect of display polarity on visual acuity and proofreading performance was investigated for younger and older adults. An advantage of positive polarity (dark characters on light background) over negative polarity (light characters on dark background) was expected for younger adults, but the effects on older adults were ambiguous. Light scatter due to residues in the senescent lens and vitreous humour could reverse the typical advantage of positive polarity. However, age-related changes lead to a decline in retinal illuminance. Brighter positive polarity displays should help to compensate for this decline and, accordingly, lead to better performance than darker negative polarity displays. Participants conducted a visual acuity test with black optotypes on white background or white optotypes on black background and performed a proofreading task in the same polarity. A positive polarity advantage was found for both age groups. The presentation in positive polarity is recommended for all ages.

**Practitioner summary:** In an ageing society, age-related vision changes need to be considered when designing digital displays. Visual acuity testing and a proofreading task revealed a positive polarity advantage for younger and older adults. Dark characters on light background lead to better legibility and are strongly recommended independent of observer's age.

**Keywords:** display polarity; age; vision changes; display design



## 1. Introduction

An important aspect in the process of digital display design is the decision regarding display polarity. Text can be presented either as dark characters on light background (positive polarity) or as light characters on dark background (negative polarity). Several studies have reported significant benefits of positive polarity displays covering performance as well as preference measures. For instance, a positive polarity advantage has been found in error rates and reading speed in a letter identification task (Bauer and Cavonius 1980), the number of transcribed letters onto paper (Radl 1980), subjective ratings on visual comfort (Saito, Taptagaporn, and Salvendy 1993; Taptagaporn and Saito 1990, 1993), text comprehension (A. H. Wang, Fang, and Chen 2003), reading speed (Chan and Lee 2005) and proofreading performance (Buchner and Baumgartner 2007). Taptagaporn and Saito (1990, 1993) tracked changes in pupil size for different illumination levels as well as for the viewing of different visual targets, such as a cathode ray tube (CRT) display, script and keyboard. They found less visual fatigue as measured by the frequency of changes in pupil size when working was accomplished with a positive than with a negative polarity display. Likewise, Saito, Taptagaporn, and Salvendy (1993) found faster lens accommodation and thus faster focusing of the eye with positive than with negative polarity displays.

However, some studies did not find significant differences between positive and negative polarity displays. Reading speed and comprehension (Cushman 1986), proofreading rate and accuracy (Creed, Dennis, and Newstead 1988; Gould et al. 1987), reading rate (Legge, Pelli et al. 1985; Legge, Rubin, and Luebker 1987), reading time, search time and subjective preference (Pastoor 1990), fatigue (Shieh 2000), visual acuity and perceived display quality (Wang and Chen 2000) and visual search performance (Ling and van Schaik 2002) have been reported not to differ as a function of display polarity. Several reasons may account for these apparent inconsistencies in the literature. First, almost all of the studies just mentioned (except those of Shieh 2000; Wang and Chen 2000) used within-subject manipulations of display polarity. A problem here is that participants may want to maintain a certain performance level and thus increase or decrease their effort in the difficult (negative polarity) or easy (positive polarity) condition, respectively (Buchner and Baumgartner 2007). This would mask any differences between conditions. Second, very small sample sizes lead to very low statistical power which makes it very unlikely to detect differences between polarity conditions (e.g. Legge, Pelli et al. 1985, with $n = 6$; Legge, Rubin, and Luebker 1987, with $n = 2$). Third, most null findings were obtained using CRT displays which may flicker and thus cause visual fatigue and decreased performance particularly in bright positive, and much less in dark negative, polarity conditions (Krueger 1984; Pawlak 1986). Flicker is no longer a problem with modern thin-film transistor liquid-crystal displays (TFT-LCDs) that represent present standards. This is why we used a between-subjects manipulation of polarity in a study with adequate sample size and TFT-LCDs.

*Corresponding author. Email: cosima.piepenbrock@hhu.de

The advantage of positive polarity displays can be explained by their typically higher luminance. Text displays with dark letters on light background are typically brighter than displays showing light letters on dark background. Higher luminance leads to a greater pupillary contraction that reduces the effects of spherical aberrations (e.g. Liang and Williams 1997; Lombardo and Lombardo 2010; Y. Wang et al. 2003) and increases the depth of field (e.g. Charman and Whitefoot 1977; Green, Powers, and Banks 1980). As a result, the focusing effort is reduced and the quality of the retinal image is improved, leading to less visual fatigue and greater legibility (but note that the inverse relationship between pupil size and retinal image quality is complicated by diffraction effects that come into play for very small pupil sizes; see Campbell and Gubisch 1966). Evidence for this explanation comes from a study by Buchner, Mayr, and Brandt (2009) who manipulated text-background polarity and overall display luminance (calculated as the weighted average of the luminance of screen pixels displaying text and background), while keeping the display contrast constant. There was no advantage of positive polarity in a proofreading task when comparing positive and negative polarity displays of equal overall luminance. Instead, display luminance affected the results, with better performance for the brighter displays. Variables other than display luminance – such as familiarity – seem to be of minor (or even no) relevance for the polarity effect.

Even though the positive polarity advantage seems to be a robust phenomenon, the empirical basis for this conclusion is limited in that it has been established mostly for younger participants in their early 20s to 30s. As will be apparent in the following section, it seems quite possible a priori that the positive polarity advantage observed for young people may not hold, or even turn into a disadvantage for older people. Whether this is the case seems important not only with respect to the scope of the polarity effect and its theoretical explanation, but also with respect to pragmatic questions such as how to present information on digital displays given the demographic change in industrialised societies.

The ageing eye shows a significant decrease in pupil diameter (i.e. senile miosis). The pupil becomes smaller at all levels of illumination (Haegerstrom-Portnoy and Morgan 2007). For instance, Loewenfeld (1979) reported a 1.60 times larger average pupil diameter for a 20-year-old than for 80-year-old participants in dim illumination conditions. As a consequence of the decreased pupil size, less light reaches the retina of the aged eye. Also, the axial thickness of the lens increases because throughout life new fibres accumulate on already existing fibres in concentrically arranged layers (Berke and Rauscher 2007). According to Weale (1989), the lens' transverse diameter increases by almost 10%, that is nearly 1 mm between the teens and the age of 60. The continuous growth throughout life leads to a reduced retinal illuminance and mechanical deformability with age. The transparency of the ageing lens also decreases in the course of a lifetime. The cloudier the lens becomes, the less light can pass through it and reach the retina. An extreme increase in the lens' optical density leads to the pathological condition of the cataract. The changes presented so far have in common that they reduce the retinal illuminance of the aged eye. In fact, a 60-year-old retina receives only one-third of the amount of light that reaches the retina of a 20-year old (Weale 1963). From this point of view one would assume that high-display luminance should be particularly advantageous to older people.

However, the blurred lens of the ageing eye is not homogeneous, and light scatter is also a problem. Over time, eye lens proteins tend to aggregate into 'randomly distributed high molecular weight clusters' (Boscia et al. 2000) that lead to intraocular light scatter. A further cause of light scatter is the vitreous humour that turns from a rather homogeneous structure during childhood to a rather heterogeneous body during old age (Sebag 1987). Originally fine and straight fibres grouped in parallel bundles become thickened, tortuous and irregular in the senescent eye (Sebag 1987). Light rays that hit those degenerated fibres cause light scatter. It is often stated (e.g. Berke and Rauscher 2007; Schierz 2011) that the light scatter does not only engender a reduction in the retinal image contrast, but also leads to increased glare sensitivity. If true, these problems may exacerbate as more light enters the eye, suggesting that high display luminance may not be beneficial, but rather detrimental to older people. The interesting question is whether such effects might reduce or eliminate the positive polarity advantage for older adults, or even reverse it to a negative polarity advantage.

A few studies exist which might be relevant to this question because the polarity effect was investigated with low-vision or older participants. For instance, Legge, Rubin et al. (1985) measured reading rates of low-vision observers for text scanned across the face of a TV monitor. Observers with corneal scattering, cataract or vitreous debris (cloudy media) were 10–15% better at reading negative than positive polarity text. No effect of polarity was found for neither low-vision observers with clear media nor for normal observers (Legge, Rubin et al. 1985). Sloan (1977) described several cases of low-vision patients who preferred using display readers with reversed contrast. Papadopoulos and Goudiras (2005) emphasised the advantages of 'reverse contrast' text for low-vision observers with cloudy ocular media and recommended adaptable tools for computer programs that offer options to change polarity for visually impaired users. In line with this recommendation, an easily accessible option to invert the display colours has been implemented on Apple's Mac OS X (since 2001) and iOS.

Westheimer et al. (2003) investigated the polarity effect in 106 patients in a general refraction clinic ranging in age from 20 to 88. All tests were conducted with optimally corrected binocular visual acuity, and patients with major ocular pathology were excluded. Visual acuity measured by normal and reversed polarity Snellen-type charts did not differ in younger adults. However, with increasing age, the patients' visual acuity improved with negative polarity Snellen-type charts, that is, white letters on a black background. The authors attributed the advantage of negative polarity displays to intraocular scatter in the aged eye that is assumed to reduce the retinal image contrast for positive polar optotypes in particular (for a detailed elaboration on the relationship between optical scatter, contrast polarity and perceived contrast, see Westheimer 2001; Westheimer and Liang 1995).

However, although plausible a priori, it is not clear that findings obtained with low-vision participants can be generalised to older adults. Furthermore, the Westheimer et al. (2003) study has serious problems. First, the visual acuity measures were compromised by a severe ceiling effect because the measurements were limited at a visual acuity of 20/15 (1.33 in Snellen Decimals), but a maximum visual acuity of 2.0 or higher is considered necessary in order to measure visual acuity in a group of normal-sighted participants (Bach 2007). Second, sequence effects are likely to have played a role because the left of two Snellen charts was always presented first which used positive polarity, whereas the negative polarity right chart was presented subsequently. Hence, it is plausible that participants' training experiences with the positive polarity chart improved performance during the subsequent visual acuity measurement with the negative polarity chart. These practice effects appear even more likely considering that for each row, both charts showed exactly the same letters.

In essence, then, although there is reason to suspect that the positive polarity advantage observed for younger adults may be reduced, eliminated or even reversed to a negative polarity advantage in older adults, it is not at all clear that this is the case. This study thus tested directly whether a positive polarity advantage exists for older adults. We also made sure to avoid the problems identified in previous investigations of the effects of polarity on performance. For that purpose, visual acuity was measured using Landolt C optotypes and a proofreading task. Landolt C optotypes allow for a pure visual acuity testing without meaningful alphanumeric characters and have several advantages as compared with Snellen letters, such as the control of guessing (for more details on the properties and advantages of Landolt C optotypes, see Bach 2007). Furthermore, it was ensured that visual acuity testing allowed for measuring a maximum visual acuity of 2.0 to prevent ceiling effects. The proofreading task has been used in previous investigations of display polarity (Buchner and Baumgartner 2007; Buchner, Mayr, and Brandt 2009) and allowed to measure the polarity effect in an everyday task and thus with greater ecological validity. A between-subjects manipulation of display polarity was chosen in order to prevent a possible performance–effort trade-off between polarity conditions as well as sequence effects. A TFT-LCD was used to present the optotypes and the text for the proofreading task. For a more comprehensive assessment beyond mere performance subjective well-being was assessed using the multidimensional mood questionnaire (Steyer et al. 1997) and a questionnaire on physical discomfort (Heuer et al. 1989).

A positive polarity advantage was expected for younger adults. A comparable positive polarity advantage for older adults would indicate that older adults' net benefit from high-illumination levels corresponds to that of younger adults. The positive polarity advantage should be reduced or even turn into a disadvantage to the degree to which glare outweighs the benefits of high illumination for older adults.



## 2. Method

### 2.1 Participants

Participants were 85 older and 84 younger adults. Participants with a history of heart attack, stroke, multiple sclerosis, brain trauma, alcoholism, Parkinson's disease or pulmonary emphysema, and those who had taken psychotropic drugs that could influence their cognitive functioning were excluded from the study. Furthermore, the eye diseases of age-related macular degeneration, clinically relevant and/or subjectively limiting cataract (but not if corrected by cataract surgery), glaucoma, diabetic retinopathy and uveitis were exclusion criteria. Two further participants were excluded from the study due to disruptions during data collection. The older adults ranged in age from 60 to 85 years ($M = 69.82$, SD $= 5.29$), the younger adults ranged in age from 18 to 33 years ($M = 22.63$, SD $= 3.26$). All participants passed a screening test for mild cognitive impairment and early dementia and showed normal age-related results (Kalbe et al. 2004). All participants were native German speakers and reported normal or corrected-to-normal visual acuity. Older adults performed better on a multiple choice vocabulary test (Lehrl 1989) than younger adults, $F(1, 166) = 70.94$, $p < 0.01$, $\eta^2 = 0.30$.[1]

### 2.2 Material and task

The experiment took place in a dark room without light sources other than the TFT-LCD and three table lamps that were placed in the corners of the room and directed towards the wall. To assess far visual acuity, the FrACT (Vs 3.7.1 as of 2011-10-27; Bach 2007) was used. The participants' task was to name the orientation of the gap in an individually presented Landolt C optotype. There were eight possible orientations (top, bottom, left, right, top left, top right, bottom left and bottom right). Participants named them accordingly. The experimenter entered the responses so that the participants could constantly gaze at the display during the forced-choice testing. In the positive polarity condition, a black Landolt C optotype was presented on white background, whereas the reversed arrangement was presented in the negative polarity condition.[2] Screen luminance equaled 350 cd/m$^2$ for white elements and 1 cd/m$^2$ for black elements (measured by a Gossen Mavolux 5032 B illuminance meter with an optional luminance attachment with Class B accuracy according to DIN 5032-7). The ambient illumination at the participants' eye position was 16 lx in the positive polarity condition and 0 lx in the negative polarity condition. The optotypes were presented on a 24-inch (1920 × 1200 pixels) TFT display of an Apple iMac computer (Apple, Inc., Cupertino, CA, USA). A chin rest ensured a constant viewing distance of 184 cm. This distance to the screen allowed measuring visual acuity up to 2.0 Snellen decimals.

The text materials for the proofreading task were presented on the same display as the visual acuity test. However, the reading distance (again ensured by a chin rest) was 50 cm. Given a luminance of 350 cd/m$^2$ for white elements and a luminance of 1 cd/m$^2$ for black elements, the text-background Michelson contrast was $c = (L_t - L_b)/(L_t + L_b) = -1.00$ for the positive polarity condition and $c = 1.00$ for the negative polarity condition. Ambient illumination at the participants' eye position was 117 lx for the positive polarity condition and 3 lx for the negative polarity condition. During the proofreading task, participants read 28 texts that were selected from workbooks used in 9th or 10th grade. Each text was 250 words long and was presented in 10 point Helvetica. Letter height was 0.34° of visual angle. The texts covered 24–29 lines. 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. The search for grammar errors forced participants to read for comprehension rather than simply skim individual words.

Short forms of the multidimensional mood questionnaire (Steyer et al. 1997) were handed out before and after the study to assess subjective well-being in three dimensions (good vs. bad mood, alertness vs. fatigue and calmness vs. agitation). Participants were instructed to consider a list of adjectives that characterise different moods (e.g. happy, alert and calm) and to rate each adjective on a 5-point scale (1: 'not at all'; 5: 'very much') in order to describe their current mood most adequately. At the same points in time, participants also completed a questionnaire on physical discomfort including scales on eyestrain, headache, muscle strain and back pain (Heuer et al. 1989). In a final questionnaire, participants described their subjective experiences during the proofreading task. Here, participants rated aspects such as glare, reflections, text sharpness and their ability to focus on the text.

### *2.3 Procedure*

Participants were tested individually. They were randomly assigned to the positive or negative polarity condition. All displays presented to a particular participant were of the same polarity.

First, the participants rated their mood state using one of the two short forms of the multidimensional mood questionnaire (Steyer et al. 1997) and filled out a questionnaire on physical discomfort (Heuer et al. 1989). Afterwards, they were seated in front of the computer at the visual screening test distance of 184 cm and were asked to put on their glasses if a correction of far visual acuity was needed. During a 3-min adaptation phase participants looked at the display that showed the first optotype and listened to auditorily presented instructions. The visual acuity test and the contrast screening were conducted consecutively with an inter-test interval of 2 min by which the participants adapted to the first optotype of the second test. Each test consisted of 30 trials. Subsequently, participants focused on the same display but at a reading distance of 50 cm. Now they were asked to put on their reading glasses if necessary. They were instructed that their task was to find as many errors as possible in a series of short texts that they would be asked to read silently. They received a training passage of text containing the different types of errors. Participants were asked to read aloud all erroneous words they would encounter 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 auditory half-time cue was presented. After 50 s, participants received an auditory instruction to name the last two words that had been read. The training could be repeated until the participants understood the task. Next, every participant received a random sequence of 28 texts. 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 again rated their mood state using the other one of the two short forms of the multidimensional mood questionnaire, the physical discomfort questionnaire and a questionnaire about their subjective experiences during the proofreading task. The dementia screening test (Kalbe et al. 2004) and a multiple choice vocabulary test (Lehrl 1989) completed the session which took about 75 min.

### *2.4 Design*

A 2 × 2 design was used with age (younger adults vs. older adults) and display polarity (positive vs. negative) as between-subjects variables. The dependent variables were the visual acuity measured by the FrACT as well as the performance in the proofreading task derived from the number of errors detected adjusted by the false alarms ($P_r$ = hit rate − false alarm rate). In order to monitor potential speed–accuracy trade-offs, participants' reading rate as measured by the amount of words read was recorded as well.

Based on previous studies (Buchner and Baumgartner 2007; Buchner, Mayr, and Brandt 2009), the polarity effect was expected to be 'large' in terms of the conventions introduced by Cohen (1988). In order to detect a large effect of display polarity, that is an effect of size $f = 0.40$ in each of the two age groups, given desired levels of $\alpha = \beta = 0.05$, data had to be collected from a sample of at least 84 participants per age group (Faul et al. 2007). We collected data from 85 older and 84 younger participants. The level of $\alpha$ was maintained at 0.05 for all statistical decisions. In order to run an ANOVA for the visual acuity scores, all individual scores were log-transformed (logVA). LogVA equals -logMAR and provides visual acuity scores with intervals that correspond to the increments in participants' sensation magnitude (Bach and Kommerell 1998).

## 3. Results

### *3.1 Visual acuity*

Figure 1 shows that visual acuity was better in the positive than in the negative polarity condition for younger and for older participants. This positive polarity advantage was smaller for older than for younger participants. Also, young participants' visual acuity scores were better than older participants' scores independent of the polarity condition. A 2 × 2 ANOVA with polarity and age as between-subjects variables showed statistically significant effects of polarity, $F(1, 163) = 69.31$, $p < 0.01$, $\eta^2 = 0.30$, and age, $F(1, 163) = 42.91$, $p < 0.01$, $\eta^2 = 0.21$. The interaction between these variables was also statistically significant, $F(1, 163) = 19.80$, $p < 0.01$, $\eta^2 = 0.11$. *Post hoc* *t*-tests revealed that the positive polarity advantage was significant for younger participants ($t(82) = 9.93$, $p < 0.01$, $d = 2.17$) and older participants ($t(81) = 2.53$, $p = 0.01$, $d = 0.58$).

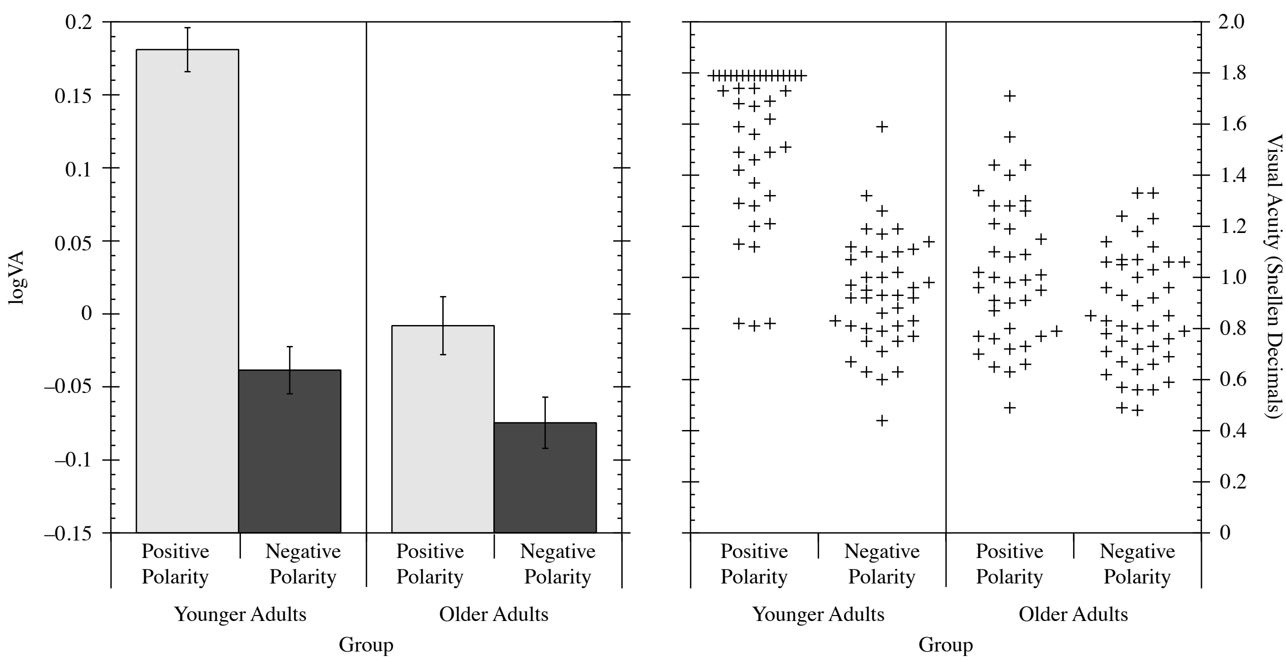


Figure 1. On the left: Mean log visual acuity (logVA) scores as a function of display polarity and age. LogVA equals log(decimal visual acuity) and -logMAR. The error bars represent the standard errors of the means. On the right: Visual acuity in Snellen decimals for the four groups. Each marker represents the visual acuity of one participant.

### *3.2 Proofreading performance*

Figure 2 shows that performance was better in the positive than in the negative polarity condition for younger and for older participants. Also, younger participants' performance was better than older participants' performance independent of the polarity variable. A 2 × 2 ANOVA with polarity and age as between-subjects variables showed statistically significant

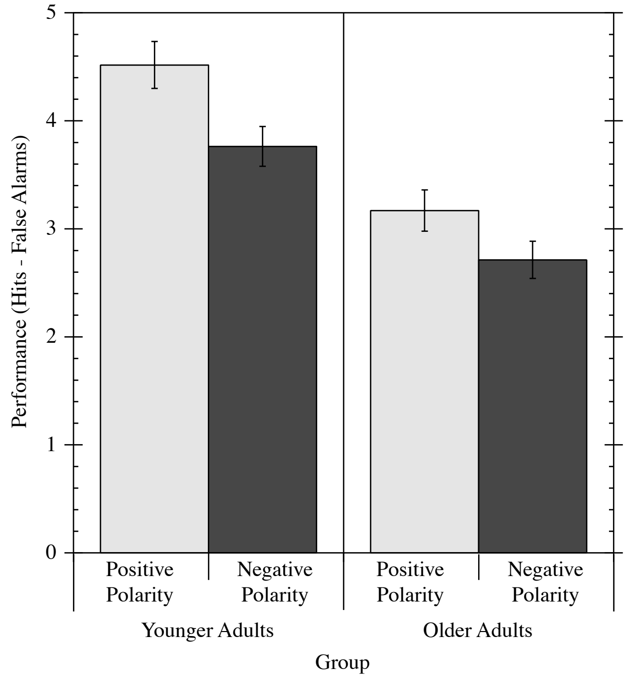


Figure 2. Mean number of errors detected per text adjusted by false alarms as a function of display polarity and age. The error bars represent the standard errors of the means.

effects of polarity, $F(1, 165) = 9.92$, $p < 0.01$, $\eta^2 = 0.06$, and age, $F(1, 165) = 38.95$, $p < 0.01$, $\eta^2 = 0.19$. There was no statistically significant interaction between these variables, $F(1, 165) = 0.60$, $p = 0.44$, $\eta^2 < 0.01$.

Reading rate was at comparable levels in the positive and in the negative polarity condition for younger as well as for older participants. A $2 \times 2$ ANOVA with polarity and age as between-subjects independent variables showed that there was a significant effect neither of polarity, $F(1, 165) = 0.16$, $p = 0.69$, $\eta^2 < 0.01$, nor of age, $F(1, 165) = 0.44$, $p = 0.51$, $\eta^2 < 0.01$. The interaction between these variables was also not significant, $F(1, 165) = 0.28$, $p = 0.60$, $\eta^2 < 0.01$ (Figure 3).

### 3.3 *Eyestrain, headache, muscle strain and back pain and subjective well-being*

Differences between pre- and post-measurements were computed for the eyestrain, headache and muscle strain/back pain scales of the physical discomfort questionnaire (Heuer et al. 1989) and for the three scores derived from the bipolar scales of the multidimensional mood questionnaire (Steyer et al. 1997). Separate $2 \times 2$ ANOVAs with polarity and age as independent variables showed that only 1 of the 18 different tests for main effects and interactions was significant, that is, the interaction between polarity and age when muscle strain and back pain pre-post difference was used as the dependent variable, $F(1, 165) = 5.22$, $p = 0.02$, $\eta^2 = 0.03$. Younger participants reported higher muscle strain and back pain after the study in the positive and in the negative polarity condition, whereas older participants reported higher muscle strain and back pain in the negative polarity condition. All other main effects or interactions were not statistically significant, all $F$'s$(1, 165) < 2.97$, $p > 0.09$, $\eta^2 < 0.02$. Considering that 1 out of 20 tests is expected to turn out significant by chance given an $\alpha$ level of 0.05 for evaluating $p$-values, it is probably best to treat this as a chance effect.

## 4. Discussion

This study investigated the effect of display polarity on visual acuity and proofreading performance for younger and older adults. For younger adults, the present experiment showed the expected positive polarity advantage in participants' visual acuity as well as in their proofreading performance. Replicating earlier findings (e.g. Bauer and Cavonius 1980; Buchner and Baumgartner 2007; Chan and Lee 2005; Radl 1980; Saito, Taptagaporn, and Salvendy 1993; Taptagaporn and Saito 1990, 1993; A. H. Wang, Fang, and Chen 2003), this validates the measures used here. Speed–accuracy trade-offs can be ruled out because participants' reading rate was comparable in both conditions. The positive polarity advantage seems to be primarily due to the typically higher overall luminance of positive polarity displays (Buchner, Mayr, and Brandt 2009).

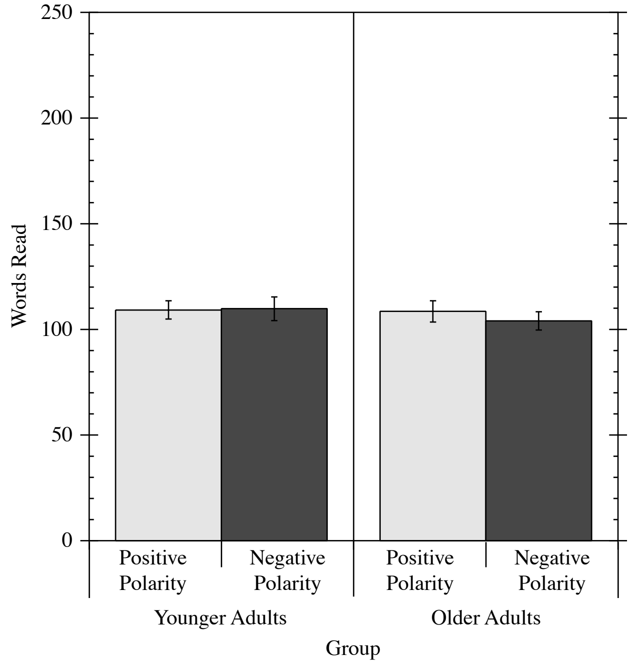


Figure 3. Mean number of words read per text as a function of display polarity and age. The error bars represent the standard errors of the means.



In the present experiment, the ambient illumination at the participants' eye position was more than 30 times higher in the positive than in the negative polarity condition. The brighter display leads to a greater pupillary contraction that, in turn, reduces the effects of spherical aberrations and increases the depth of field (e.g. Charman and Whitefoot 1977; Green, Powers, and Banks 1980; Liang and Williams 1997; Lombardo and Lombardo 2010; Wang et al. 2003).

There seemed to be reason to suspect that the additional illumination would increase the intraocular light scatter in the aged eye which, in turn, could reduce the retinal image contrast. As a consequence, visual acuity and proofreading performance should suffer, eliminating the positive polarity advantage or even reversing it such that negative polarity is associated with better performance than positive polarity (Westheimer et al. 2003). However, this was not the case. A positive polarity advantage was observed for older adults in both visual acuity and proofreading performance. As with younger adults, there was no evidence of speed–accuracy trade-offs which could have complicated the interpretation of the proofreading results.

These results are contrary to those of Westheimer et al. (2003) who reported better visual acuity for older adults with negative polarity Snellen-type charts. However, as pointed out in the introduction, the results of that study cannot be interpreted because of its serious methodical problems. At first sight, the present findings may also seem to be in conflict with a negative polarity advantage observed with low-vision adults (e.g. Legge, Rubin et al. 1985; Sloan 1977). However, adults with pathological changes of the eye, such as clinically relevant and/or subjectively limiting cataract, were excluded from this study because the focus here was on age-related, non-pathological changes in the eye (but note that participants with a history of cataract surgery were not excluded). Thus, although increased light scatter may indeed impede the legibility of positive polarity displays for adults with pathological opafication of the lens or the vitreous humour, it seems to play a negligible role for the elderly without clinically relevant and/or subjectively limiting visual impairments due to cataract or other eye diseases.[3] Overall, older adults with clear vision certainly benefit from positive polarity displays.

However, for the visual acuity measurements, the positive polarity advantage was clearly smaller for older than for younger adults (with effect sizes of $d = 0.58$ and $d = 2.17$, respectively). This seems to indicate that older adults' visual capacity might, at least to some degree, be affected by an increased level of glare caused by intraocular light scatter. Although this glare effect was not strong enough to abolish the positive polarity advantage, let alone to revert it into a negative polarity advantage for older adults, it seems to have reduced the beneficial effect of the brighter positive polarity display.

If this reasoning is correct, the question remains why the age-related reduction of the positive polarity advantage was observed for the visual acuity but not for the proofreading task. Judgements of Landolt C optotypes and a forced-choice testing procedure that controls for guessing rates do not provide many opportunities for influences beyond perceptual factors which thus leads to a very sensitive measure of the individual's sensory threshold that is primarily, if not exclusively, determined by bottom-up perceptual processes. In contrast, proofreading performance probably implies perception somewhat above the sensory threshold and presumably depends to a larger extent on factors beyond the quality of the retinal image, such as motivation and practice. Thus, age-related increases in light scatter may be captured by very sensitive measures of visual acuity thresholds, but they might simply be too small to play an observable role in a more complex task such as proofreading (which, at least descriptively, shows a slightly smaller positive polarity advantage for older than for younger adults).

Whatever the cause of difference in the size of the polarity effect, the important result of this study is that a positive polarity advantage was observed for both younger and older adults. Consequently, we recommend to present dark characters on light background in digital displays independent of the target audience's age.

## Acknowledgements

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## Notes

1. Due to data loss, the statistical analysis for the multiple choice vocabulary test is based on $N = 168$.
2. A contrast test was conducted subsequent to the visual acuity test. Participants' task was identical to the visual acuity test: they named the orientation of the gap in an individually presented Landolt C optotype. In contrast to the visual acuity test, Landolt C optotypes in the contrast test (displayed in a size that corresponds to an acuity of $0.1_{\text{decimal}}$) were presented in a sequence of descending contrasts with up to five presentations per contrast level. Results of the contrast sensitivity measurements as well as the results of a final questionnaire regarding subjective experiences during the proofreading task will not be reported because they are not relevant for the research questions addressed in this paper.
3. It is conceivable that the positive polarity advantage would have been decreased for older adults if cataract patients had been tested as well.



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