Ergonomische Gestaltung digitaler Anzeigen für jüngere und ältere Erwachsene
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Optimierung der Lesbarkeit durch eine positiv polare Textdarstellung

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Cosima Piepenbrock

aus Düsseldorf

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Referent:	PD Dr. Susanne Mayr
Korreferent:	Prof. Dr. Axel Buchner

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Zusammenfassung

Die in der vorliegenden Arbeit vorgestellten Studien untersuchten den Effekt der Polarität auf die Lesbarkeit digitaler Anzeigen. In allen Studien konnte ein Vorteil positiver Polarität, das heißt dunkler Schrift auf hellem Hintergrund, im Vergleich zur Darstellung in negativer Polarität nachgewiesen werden. Die Experimente 1 und 2 untersuchten die Wirkmechanismen des Vorteils positiv polarer Textpräsentationen mittels einer Korrekturleseaufgabe. Mögliche Erklärungsansätze umfassen die größere Vertrautheit für dunkle Schrift auf hellem Hintergrund, die größere Ressourcenaufwendung der Retina für die Enkodierung negativer Kontraste und die höhere Bildschirmluminanz positiv polarer Testdarstellungen. Beide Studien stützen die Bildschirmluminanz-Hypothese. Die helleren positiv polaren Anzeigen führen zu einer stärkeren Pupillenverengung (Experiment 2) und somit zu einer höheren Sehschärfe durch verringerte sphärische Aberrationen und einer erhöhten Schärfentiefe. Daher zeigt sich der Vorteil positiver Polarität verstärkt bei der Wahrnehmung feiner Details (Experiment 1). Experiment 3 untersuchte den Effekt der Polarität bei jüngeren und älteren Personen. Angesichts altersbedingter Veränderungen im Auge und Befunden aus Untersuchungen sehbehinderter Personen schien die Hypothese plausibel, dass der Vorteil positiv polarer Textdarstellungen für ältere Personen verschwände oder sich sogar umkehre und die Darstellung heller Schrift auf dunklem Hintergrund vorteilhaft sei. Experiment 3 zeigte mittels Sehschärfetestungen und einer Korrekturleseaufgabe, dass die allgemeine Empfehlung, Text in Form dunkler Schrift auf hellem Hintergrund darzustellen, sowohl für jüngere als auch für ältere normalsichtige Betrachter Gültigkeit besitzt.

Abstract

The present studies investigated the effect of polarity on the legibility of digital displays. All studies showed a consistent positive polarity advantage, that is, an advantage of dark characters on light background. Experiments 1 and 2 investigated the underlying mechanisms of the advantage of positive polarity text presentations using a proofreading task. Possible alternative hypotheses refer to the higher familiarity of positive polarity text presentations, the higher allocation of retinal resources to the processing of dark spots on light background than to light spots on dark background and the typically higher display luminance of positive polarity displays. Both studies strengthen the display luminance hypothesis. The higher luminance of positive polarity displays leads to a stronger pupillary constriction (Experiment 2) and thus reduces the effects of spherical aberrations and increases the depth of field. This fits nicely with the fact that the positive polarity advantage is particularly pronounced when the task requires the perception of fine details (Experiment 1). Experiment 3 investigated the effect of display polarity on visual acuity and proofreading performance for younger and older adults. Considering age related vision changes and findings with low-vision participants there was 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. However, Experiment 3 showed that the presentation of dark characters on light background is recommended independent of an observer's age.

1. Einleitung

Digitale Anzeigen sind aus dem Alltag des 21. Jahrhunderts nicht mehr wegzudenken. So vergeht im „digitalen Zeitalter“ selten ein Tag, an dem der Mensch nicht in Kontakt mit einem digitalen Medium tritt. Verband man in den 1980er Jahren mit dem Begriff der Digitalisierung vor allem die „Computerisierung der Arbeitswelt“ (Schuhmann, 2012) sowie den sukzessiven Einzug von Computern in Privathaushalte[1], so wird der Umgang mit digitalen Medien heutzutage von vielen als selbstverständlicher Bestandteil ihres Lebens wahrgenommen. In einer Zeit, in der Informationen überall und zu jeder Zeit verfügbar sein sollen, sind also unterschiedliche Personengruppen unmittelbar auf die Informationsvermittlung über digitale Anzeigen angewiesen (Ziefle, 2009).

Durch den Einzug digitaler Medien in die verschiedensten Bereiche des Lebens und die Vielfältigkeit der Nutzer stiegen die Anforderungen an die Anzeigenqualität. Die Qualität digitaler Anzeigen hat praktische Implikationen für das alltägliche Leben unzähliger Personen. Sie ist beispielsweise ausschlaggebend für die langfristige Gesundheit und Produktivität der Menschen, die einen Großteil des Tages vor einem Computermonitor sitzen und Bildschirmarbeit verrichten, sowie für die unmittelbare Sicherheit eines Autofahrers, der während der Fahrt auf die Lesbarkeit der digitalen Anzeige seines Navigationssystems angewiesen ist, und auch für die sichere und autarke Teilnahme einer älteren Person am gesellschaftlichen Leben, die in der Lage sein muss, die Anzeige eines Bankterminals zu lesen oder die Zuginformation einer digitalen Bahnhofsanzeige zu erkennen.

Die Qualität dieser Anzeigen hängt im Wesentlichen von zwei ausschlaggebenden Faktoren ab, der zugrundeliegenden Technologie und einer ergonomischen Anzeigengestaltung. Die Weiterentwicklungen der letzten Jahrzehnte im Bereich der Bildschirmtechnologie sind zahlreich. Hervorzuheben ist hier vor allem die Entwicklung der Flachbildschirme mit LCD-Technologie (LCD = liquid crystal display), die sich weitestgehend gegen CRT-Monitore (CRT = cathode ray tube), sogenannte Röhrenmonitore, durchsetzten. Ein wichtiges Qualitätskriterium der CRT-Monitore ist ihre Bildwiederholungsrate. Sie entspricht dem reziproken Wert der Zeit, die für die Produktion eines vollständigen Bildschirmbildes erforderlich ist, und muss entsprechend hoch sein, damit ein flimmerfreies Bild erzeugt werden kann. Eine hohe Bildwiederholungsrate ist nötig, da die Phosphorschicht der einzelnen Bildpunkte pro Zyklus durch einen Elektronenstrahl neu zum Leuchten angeregt wird. Einzelne Bildpunkte werden also kurz aktiviert und verblassen anschließend immer mehr. So wird beispielsweise laut Dortmunder Standard eine Bildwiederholungsrate von mindestens 95 Hz empfohlen (Bauer, 1989). In diesem Frequenzbereich kann das menschliche visuelle System den temporalen Wechsel zwischen hellem (aktiviertem) und dunklem (verblasstem) Bild nicht mehr auflösen (*Flimmerfusionsfrequenz*), und störendes Flimmern kann ausgeschlossen werden. Die Problematik eines flimmernden Bildes tritt bei LCD-Monitoren nicht auf. Aufgrund ihrer Flüssigkristalltechnologie zeigen sie stets ein flimmerfreies Bild und sind somit weniger belastend für die Augen. Polarisiertes Licht wird durch eine Schicht aus Flüssigkristallen geleitet und je nach elektrischer Aufladung an einem Bildpunkt hindurchgelassen oder nicht. Farbe wird durch unterschiedliche Filtermasken erzeugt. Zusätzliche Weiterentwicklungen wie die Schriftenglättung mit Hilfe von Subpixel-Rendering haben die Qualität der Darstellung außerdem verbessert.

Neben der zugrundeliegenden Bildschirmtechnologie determinieren die Charakteristika der Anzeigengestaltung die Lesbarkeit digitaler Anzeigen. So definiert die DIN EN ISO 9241-303 (2011) beispielsweise für eine ergonomische Gestaltung digitaler Anzeigen Anforderungen bezüglich folgender Faktoren: Leuchtdichtekontrast, Bildpolarität, Zeichenhöhe, Konstanz der Textgröße, Zeichenstrichbreite, Verhältnis Zeichenbreite zu Zeichenhöhe, Zeichenformat, Zeichenabstand, Wortabstand und Zeilenabstand. Die vorliegende Arbeit greift den Aspekt der Bildpolarität, im Folgenden *Anzeigenpolarität* oder *Polarität* genannt, im Detail auf.

Text kann in Form dunkler Schrift auf einem hellen Hintergrund (*positive Polarität*) dargestellt werden oder in Form heller Schrift auf einem dunklen Hintergrund (*negative Polarität*). Die Darstellung dunkler Schrift auf hellem Hintergrund wird auch als „negativer Kontrast“ bezeichnet, da der Kontrast $c = (L_T - L_H) / (L_T + L_H)$ negativ wird, wenn die Textluminanz, L_T, geringer ist als die

Hintergrundluminanz, L_H [2]. Die Luminanz (cd/m^2) kann als Maß für die wahrgenommene Helligkeit einer Fläche verstanden werden. Sie beschreibt den Lichtstrom, der von einer Fläche ausgestrahlt wird und unter einem gegebenen Sehwinkel das Auge erreicht.

Die bisherige Datenlage zum Effekt der Polarität ist umfangreich und zeigt ein gemischtes Befundmuster. Diverse Studien berichteten einen Vorteil positiv polarer Text-Hintergrund-Präsentationen. Diese umfassten objektive Leistungsmaße wie zum Beispiel Fehlerrate und Lesegeschwindigkeit bei der Buchstabenerkennung (Bauer & Cavonius, 1980), Anzahl auf Papier transkribierter Buchstaben (Radl, 1980), Textverständnis (A. H. Wang, Fang, & Chen, 2003), Lesegeschwindigkeit (Chan & Lee, 2005), Korrekturleseleistung (Buchner & Baumgartner, 2007), Wort-Nicht-Wort-Unterscheidung (Mayr & Buchner, 2010) und visuelle Suche (Tsang, Chan, & Yu, 2012). Der Vorteil positiver Polarität zeigte sich zudem in subjektiven Präferenzmaßen wie beispielsweise Bewertungen des visuellen Komforts (Saito, Taptagaporn, & Salvendy, 1993; Taptagaporn & Saito, 1990, 1993).

In Studien, in denen sich keine signifikanten Unterschiede zwischen positiv und negativ polaren Darstellungen zeigten, wurden unter anderem Lesegeschwindigkeit und -verständnis (Cushman, 1986), Korrekturlesegeschwindigkeit und -genauigkeit (Creed, Dennis, & Newstead, 1988; Gould et al., 1987), Leserate (Legge, Pelli, Rubin, & Schleske, 1985; Legge, Rubin, & Luebker, 1987), Lesezeit, Suchzeit und subjektive Präferenz (Pastoor, 1990), Müdigkeit (Shieh, 2000), Sehschärfe und wahrgenommene Bildschirmqualität (A. H. Wang & Chen, 2000) sowie visuelle Suchleistung (Ling & van Schaik, 2002) untersucht. Es ist jedoch anzunehmen, dass einige dieser Nullbefunde auf geringe Stichprobengrößen zurückzuführen sind, welche wiederum zu einer geringen Teststärke führten und das Auffinden von Unterschieden zwischen den Polaritätsbedingungen unwahrscheinlich machten (z.B. Legge, Pelli, et al., 1985, mit $n = 6$; Legge et al., 1987, mit $n = 2$). In einem Großteil der zuvor genannten Studien, die Nullbefunde erbrachten, wurden darüber hinaus CRT-Monitore für die Stimuluspräsentation verwendet. Diese Monitore weisen typischerweise eine Bildwiederholungsrate von 60 Hz auf und neigen daher bei hellen Bildschirmanzeigen zu einem für das Auge unangenehmen Flimmern. Da positiv polare Anzeigen in der Regel heller sind als negativ polare Anzeigen, stört das Flimmern besonders in positiv polaren Lesebedingungen und beeinträchtigt die Leistung stärker im Vergleich zu dunkleren, negativ polaren Textpräsentationen (Krueger, 1984; Pawlak, 1986). Moderne LCD-Monitore sind von dieser Problematik nicht mehr betroffen.

Interessant ist, dass Befunde, die einen Vorteil negativ polarer Anzeigen für normalsichtige Personen berichten, nicht vorliegen. Folglich kann in der Gesamtschau angenommen werden, dass bei Verwendung moderner Bildschirmtechnik eine positiv polare Textdarstellung von Vorteil ist und zu besserer Lesbarkeit der Anzeige führt im Vergleich zu einer negativ polaren Textdarstellung.

Für den Vorteil positiver Polarität gibt es verschiedene Erklärungsansätze, die sich nicht gegenseitig ausschließen. Aufgrund der starken Verbreitung positiv polar dargestellter Texte – insbesondere im Bereich der Printmedien – ist dunkle Schrift auf hellem Hintergrund um einiges vertrauter als eine negativ polare Textdarstellung. Es ist daher denkbar, dass die beim Lesen involvierten kognitiven Prozesse für das Erkennen dunkler Buchstaben auf einem hellen Hintergrund optimiert sind (Hall & Hanna, 2004). Außerdem könnte die größere Ressourcenaufwendung der Retina für die Enkodierung negativer Kontraste für den Vorteil positiver Polarität verantwortlich sein (Ratliff, Borghuis, Kao, Sterling, & Balasubramanian, 2010).

Einen weiteren Erklärungsansatz bietet die Bildschirmluminanz, die typischerweise bei der Darstellung dunkler Schrift auf hellem Hintergrund höher ist als bei heller Schrift auf dunklem Hintergrund. Es wird daher angenommen, dass sich die Pupille aufgrund des höheren Lichteinfalls stärker verengt, wenn das Auge auf einen positiv polar gestalteten Bildschirm gerichtet ist. Eine stärkere Pupillenkontraktion führt wiederum zu verringerten Effekten sphärischer Aberration (Liang & Williams, 1997; Lombardo & Lombardo, 2010; Y. Wang, Zhao, Jin, Niu, & Zuo, 2003). Das Ausmaß sphärischer Aberrationen steigt mit der vierten Potenz des Pupillendurchmessers an. Dies bedeutet, dass eine Reduzierung des Pupillendurchmessers um die Hälfte zu einer 16-fachen Abnahme sphärischer Aberrationen führt (American Academy of Ophthalmology, 2009). Als Folge verringerter sphärischer Aberrationen steigt die Schärfentiefe des Auges bei verengter Pupille (Charman & Whitefoot, 1977; Green, Powers, & Banks, 1980). Der dioptrische Bereich, in dem sich die Qualität des retinalen Abbilds nicht merklich ändert, wird somit größer. Eine erhöhte Schärfentiefe führt immer dann zu einem schärferen retinalen Abbild, wenn das Auge nicht perfekt fokussiert ist. Zu dieser Akkommodationsungenauigkeit (*accommodative lag*) kommt es typischerweise bei Aufgaben, die das Nahsehen beanspruchen, wie zum Beispiel beim Lesen von Text. Mögliche Einbußen in der Sehschärfe durch die Akkommodationsungenauigkeit können durch eine Reduzierung des Pupillendurchmessers und die damit einhergehende erhöhte Schärfentiefe abgeschwächt werden (Lopez-Gil et al., 2013). Eine positiv polare Textpräsentation sollte demnach zu einer erhöhten Toleranz gegenüber Akkommodationsfehlern beim Nahsehen führen und somit zu einer besseren Textlesbarkeit.

Eine erhöhte Sehschärfe und bessere Detailwahrnehmung bei reduzierter Pupillengröße konnte von Berman et al. (1996) nachgewiesen werden. Es ist allerdings zu beachten, dass eine Verringerung des Pupillendurchmessers nur in Grenzen von Vorteil ist. Bei sehr geringen Pupillendurchmessern leidet die Abbildungsqualität aufgrund einer verstärkten Lichtbeugung am Pupillenrand, der sogenannten Diffraktion. So berichteten Campbell und Gubisch (1966) einen optimalen Pupillendurchmesser von 2.4 mm, bei welchem sich die nachteiligen Effekte der Diffraktion einerseits und der sphärischen Aberrationen andererseits am günstigsten zueinander verhalten.

Empirisch untermauert wurde die Bildschirmluminanz-Hypothese durch eine Studie von Buchner, Mayr und Brandt (2009). Sie manipulierten die Anzeigenpolarität und die Gesamtluminanz des Bildschirms bei konstantem Kontrast unabhängig voneinander. Die Gesamtluminanz des Bildschirms wurde dabei als gewichtetes Mittel der Helligkeit der Text und Hintergrund darstellenden Bildschirmpixel bestimmt. Es zeigte sich im Vergleich der beiden Polaritätsbedingungen kein Vorteil positiver Polarität beim Korrekturlesen, wenn die Gesamthelligkeit der Anzeigen gleich gehalten wurde. Stattdessen berichteten die Autoren, dass die Bildschirmluminanz der entscheidende

Faktor war und die Korrekturleseleistung bei hellen Bildschirmen signifikant besser als bei dunklen war. Es scheint also, dass der Vorteil positiv polarer Textpräsentationen auf einen Helligkeitseffekt zurückgeht, und dass andere Faktoren wie zum Beispiel eine größere Vertrautheit für die Darstellung dunkler Schrift auf hellem Hintergrund eine untergeordnete oder gar keine Rolle spielen.

Gleichwohl ist eine unabhängige Testung der Bildschirmluminanz-Hypothese wünschenswert. So fällt zum Beispiel auf, dass Buchner et al. (2009) Kontrastwerte von -0.30 bzw. 0.30 für die positiv beziehungsweise negativ polare Textdarstellung wählten. Dieser geringe Kontrast zwischen Text und Hintergrund führt zu einer eher unnatürlichen Lesesituation, die das Lesen künstlich erschwert (Ziefle, 2009). Um eine höhere ökologische Validität zu erreichen, sollte das Textmaterial kontrastreicher präsentiert werden (Nielson, 1999). Beispielsweise empfiehlt die DIN EN ISO 9241-303 (2011) einen Mindestkontrast von $c = 0.5$. Demnach ist es indiziert, schwarzen Text auf einem weißen Hintergrund beziehungsweise weißen Text auf einem schwarzen Hinterrund darzustellen und somit weiter auseinander liegende Graustufen zu verwenden. Dieser Ansatz der Operationalisierung wurde in den im Folgenden dargestellten Studien gewählt.

2. Experiment 1

Eine Möglichkeit, die Bildschirmluminanz-Hypothese zu testen, ist durch die Untersuchung des Zusammenspiels von Anzeigenpolarität und Schriftgröße. Unter der Annahme, dass die typischerweise höhere Bildschirmluminanz bei positiv polaren Anzeigen zu einer Reduktion des Pupillendurchmessers führt, was geringere sphärische Aberrationen und eine erhöhte Toleranz für Akkommodationsungenauigkeiten impliziert, wird antizipiert, dass der Vorteil positiver Polarität vor allem dann zutage tritt, wenn erhöhte Detailwahrnehmung notwendig ist. Das Erkennen feiner Details ist beim Lesen umso mehr von Bedeutung, je kleiner die Schriftgröße ist. Insofern sollte der Vorteil positiver Polarität mit abnehmender Schriftgröße zunehmen. Sollten hingegen andere Faktoren wie zum Beispiel die stärkere Vertrautheit für eine positiv polare Textpräsentation ausschlaggebend für den Vorteil positiver Polarität sein, wäre zu erwarten, dass sich der Vorteil positiver Polarität über die verschiedenen Schriftgrößen hinweg in konstanter Größe zeigt. Dieser Überlegung liegt der Befund zugrunde, dass die Lesbarkeit von Schrift mit ansteigender Schriftgröße zunimmt (Bernard, Chaparro, Mills, & Halcomb, 2003; Fagan, Westgate, & Yolton, 1986; Griffing & Franz, 1896; Luckiesh & Moss, 1939; Miyao, Hacisalihzade, Allen, & Stark, 1989). Die Lesbarkeit kleiner Schriften ist durch die Sehschärfe begrenzt (Smith, 1979). Folglich sollte im Besonderen die Lesbarkeit kleiner Schriften beeinträchtigt werden, wenn die Sehschärfe durch eine Textpräsentation in negativer Polarität reduziert wird. Die Prüfung dieser Hypothese war Gegenstand des ersten Experiments.

Die Teilnehmer lasen jeweils 40 ausschließlich positiv oder negativ polar dargestellte Texte in einem abgedunkelten Raum. Der Text-Hintergrund-Kontrast (gemessen am Monitor ohne Berücksichtigung der Umgebungsbeleuchtung) betrug c = (1 cd/m^2 - 342 cd/m^2) / (1 cd/m^2 + 342 cd/m^2) = -1 in der positiv polaren Bedingung (schwarzer Text auf weißem Hintergrund) und c = 1 in der negativ polaren Bedingung (weißer Text auf schwarzem Hintergrund). In der positiv polaren Bedingung wurde am Ort des Auges des Betrachters eine Umgebungsbeleuchtung von 116 lx gemessen und von 4 lx in der negativ polaren Bedingung. Für jeden Teilnehmer wurden jeweils zehn der 40 Texte zufällig einer von vier Schriftgrößen zugeordnet: 8 pt Helvetica (mit einer x-Höhe von 0.22° Sehwinkel bei 50 cm Lesedistanz zum Bildschirm), 10 pt Helvetica (0.25°), 12 pt Helvetica (0.31°) und 14 pt Helvetica (0.34°). Die Texte wurden randomisiert präsentiert und umfassten jeweils 250 Wörter. Jeder Text enthielt acht orthographische Fehler und sechs Grammatikfehler. Die Teilnehmer wurden gebeten, den Text leise zu lesen und fehlerhafte Wörter laut zu benennen. Nach einer Präsentationsdauer von 50 s erhielten sie die Instruktion, die zwei zuletzt gelesenen Wörter laut zu benennen. Nachdem die Studienteilnehmer alle Texte gelesen hatten, füllten sie einen papierbasierten Fragebogen zu ihren subjektiven Empfindungen während der Korrekturleseaufgabe aus.

Die Korrekturlesegenauigkeit[3] war in der Bedingung positiver Polarität über alle Schriftgrößen hinweg besser als in der negativ polaren Bedingung, und mit zunehmender Schriftgröße wurden mehr Fehler gefunden. Zudem wurde der Vorteil positiver Polarität mit abnehmender Schriftgröße größer (Abbildung 1 in Piepenbrock, Mayr & Buchner, in press). Eine 2 × 4 MANOVA mit Polarität als Gruppenfaktor und Schriftgröße als messwiederholtem Faktor zeigte statistisch signifikante Effekte der Polarität, $F(1, 158) = 9.34$, $p < .01$, $\eta^2 = .06$, und Schriftgröße, $F(3, 156) = 83.66$, $p < .01$, $\eta^2 = .62$. Die Interaktion zwischen beiden Faktoren erreichte ebenfalls statistische Signifikanz, $F(3, 156) = 3.16$, $p = .03$, $\eta^2 = .06$. Im Besonderen interagierte die lineare Kontrastkomponente der Schriftgrößenvariable mit dem Faktor der Polarität, $F(1, 158) = 8.92$, $p < .01$, $\eta^2 = .05$ – ein Hinweis darauf, dass der Vorteil positiver Polarität mit abnehmender Schriftgröße linear ansteigt. Die Interaktionen zwischen der Polarität und der quadratischen und kubischen Komponente der Schriftgrößenvariable wurden nicht signifikant, beide $Fs < 1$.

Die Lesegeschwindigkeit fiel in der Bedingung positiver Polarität über alle Schriftgrößen hinweg höher aus als in der negativ polaren Bedingung, und mit ansteigender Schriftgröße wurden mehr Wörter gelesen. Zudem wurde der Vorteil positiver Polarität mit abnehmender Schriftgröße größer (Abbildung 2 in Piepenbrock, Mayr & Buchner, in press). Eine 2 × 4 MANOVA mit Polarität als Gruppenfaktor und Schriftgröße als messwiederholtem Faktor zeigte, dass der Effekt der Polarität das festgelegte Signifikanzniveau knapp verfehlte, $F(1, 158) = 2.60$, $p = .06$, $\eta^2 = .02$. Der Effekt der Schriftgröße, $F(3, 156) = 15.86$, $p < .01$, $\eta^2 = .23$, und die Interaktion zwischen den Faktoren erreichten statistische Signifikanz, $F(3, 156) = 4.70$, $p < .01$, $\eta^2 = .08$. Im Besonderen interagierte die lineare Kontrastkomponente der Schriftgrößenvariable mit dem Faktor der Polarität, $F(1, 158) = 10.61$, $p < .01$, $\eta^2 = .06$ – ein Hinweis darauf, dass der Vorteil positiver Polarität mit abnehmender Schriftgröße linear ansteigt. Die Interaktionen zwischen der Polarität und der quadratischen und kubischen Komponente der Schriftgrößenvariable wurden wie schon für die Variable der Korrekturlesegenauigkeit nicht signifikant, beide $Fs < 1$.

Im Nachbefragungsbogen (Tabelle 1 in Piepenbrock, Mayr & Buchner, in press) zeigten sich zwischen den Polaritätsbedingungen keine signifikanten Unterschiede in der subjektiven Einschätzung verschiedener Aspekte der Textlesbarkeit wie zum Beispiel der Fokussierbarkeit auf den Text. Dieses Ergebnis ist besonders deshalb erwähnenswert, da sich in den objektiven Performanzmaßen ein klarer Vorteil der positiven Polarität zeigte. Die Teilnehmer berichteten in der negativ polaren Bedingung jedoch eine stärkere Unschärfe des Texts und höhere Schwierigkeit beim Springen von einer Textzeile zur nächsten als in der positiv polaren Bedingung. Zudem schilderten sie eine stärkere Blendung in der positiv polaren Bedingung im Vergleich zur negativ polaren Bedingung.

In Experiment 1 zeigte sich also erwartungsgemäß ein Vorteil positiver Polarität in Form besserer Korrekturleseleistung, das heißt einer höheren Korrekturlesegenauigkeit und Lesegeschwindigkeit für Text, der in dunkler Schrift auf hellem Hintergrund präsentiert wurde als für Text in heller Schrift auf dunklem Hintergrund. Dieses Befundmuster stimmt mit vorherigen Studien überein (z.B. Bauer & Cavonius, 1980; Buchner & Baumgartner, 2007; Chan & Lee, 2005; Mayr & Buchner, 2010; Radl, 1980; Taptagaporn & Saito, 1990, 1993; Tsang et al., 2012; A. H. Wang et al., 2003). Gleiches gilt für den Befund, dass größere Schriftgrößen zu besserer Lesbarkeit und somit zu einer höheren Korrekturlesegenauigkeit und Lesegeschwindigkeit führen (z.B. Bernard et al., 2003; Fagan et al., 1986; Griffing & Franz, 1896; Luckiesh & Moss, 1939; Miyao et al., 1989; Smith, 1979).

Das für die Hypothesentestung relevanteste Ergebnis des Experiments ist, dass der Vorteil positiver Polarität mit abnehmender Schriftgröße linear anstieg. Dieses Ergebnis wird von der Bildschirmluminanz-Hypothese vorhergesagt (Buchner et al., 2009). Es wird angenommen, dass die typischerweise höhere Bildschirmluminanz positiv polarer Anzeigen zu einer stärkeren Verengung der Pupille führt, welche wiederum sphärische Aberrationen reduziert und die Schärfentiefe erhöht (z.B. Charman & Whitefoot, 1977; Green et al., 1980; Liang & Williams, 1997; Lombardo & Lombardo, 2010; Lopez-Gil et al., 2013; Y. Wang et al., 2003). Dies ermöglicht eine bessere Detailwahrnehmung, die vor allem beim Lesen kleiner Schriften von Bedeutung ist (Smith, 1979). Die nachgewiesene signifikante Interaktion zwischen Polarität und Schriftgröße unterstützt somit die Bildschirmluminanz-Hypothese und widerspricht der Annahme, dass andere Faktoren wie zum Beispiel eine größere Vertrautheit für dunkle Schrift auf hellem Hintergrund für den Vorteil positiv polarer Anzeigen verantwortlich sind. Spielten diese übrigen Faktoren eine entscheidende Rolle, hätte sich der Vorteil positiver Polarität unabhängig von der Schriftgröße zeigen sollen. Dies war nicht der Fall.

3. Experiment 2

Um die Bedeutung des Pupillendurchmessers für den Vorteil positiver Polarität im Detail zu verstehen, ist es ferner wünschenswert, die Bildschirmluminanz-Hypothese mit konkreten physiologischen Daten zu stützen. So bleibt festzuhalten, dass, obwohl der Vorteil positiver Polarität ein robuster Effekt ist, der Großteil der Studien zum Polaritätseffekt auf Verhaltens- und Präferenzmaßen basiert und die Annahme der verstärkten Pupillenkontraktion bei positiv polaren Anzeigen weitgehend theoretisch begründet ist. Wenige Studien untersuchten den Einfluss der Anzeigenpolarität auf die Pupillengröße direkt. Miyao et al. (1992) und Taptagaporn und Saito (1990, 1993) berichteten einen kleineren Pupillendurchmesser bei der Betrachtung positiv polarer Anzeigen als bei negativ polaren Darstellungen. In beiden Studien wurde der Pupillendurchmesser allerdings während sehr simpler Aufgaben gemessen. In den Untersuchungen von Miyao et al. (1992) betrachteten die Teilnehmer ausschließlich positiv und negativ polar dargestellte Kreise. Die Teilnehmer der Studie von Taptagaporn und Saito (1990, 1993) führten eine Zählaufgabe durch oder blickten abwechselnd auf verschiedene Zielreize (einen CRT-Monitor, eine ausgedruckte Textseite, eine Computertastatur). Es ist also unklar, ob sich die Ergebnisse der beiden Studien auf komplexere Aufgaben mit höherem Anwendungsbezug wie zum Beispiel das Lesen von Text generalisieren lassen.

In Experiment 2 wurde daher der Einfluss der Anzeigenpolarität auf die Pupillengröße direkt durch eine kontinuierliche Vermessung der Pupille der Teilnehmerinnen und Teilnehmer während des Korrekturlesens positiv und negativ polar dargestellter Texte untersucht. Ziel des Experiments war es, die zuvor meist implizit getroffene Annahme eines verringerten Pupillendurchmessers bei positiv im Vergleich zu negativ polarer Textdarstellung unmittelbar zu untersuchen und somit eine empirisch fundierte Basis für die Bildschirmluminanz-Hypothese zu schaffen. Um eine möglichst hohe ökologische Validität der Ergebnisse zu gewähren, wurde die Pupillenmessung während einer anwendungsorientierten Korrekturleseaufgabe (Buchner & Baumgartner, 2007; Buchner et al., 2009) durchgeführt.

Laut Bildschirmluminanz-Hypothese sollte der Pupillendurchmesser beim Lesen dunkler Schrift auf hellem Hintergrund aufgrund der höheren Bildschirmluminanz positiv polarer Anzeigen geringer sein als beim Lesen heller Schrift auf dunklem Hintergrund. Sollte die Pupillenverengung bei positiv polarer Textpräsentation nicht stärker ausgeprägt sein als bei negativ polaren Anzeigen, ist die Bildschirmluminanz-Hypothese zu verwerfen. Zudem wurde ein Vorteil positiver Polarität in der Korrekturleseleistung, das heißt in der Korrekturlesegenauigkeit und der Lesegeschwindigkeit, erwartet.

Aufbau und Ablauf des Experiments waren größtenteils identisch zu Experiment 1. Änderungen in Experiment 2 werden im Folgenden dargestellt. Die Luminanz (gemessen am Monitor ohne Berücksichtigung der Umgebungsbeleuchtung) betrug 329 cd/m^2 für weiße Bildschirmelemente und 1 cd/m^2 für schwarze Elemente. Die Messung der Umgebungsbeleuchtung am Ort des Auges des Betrachters ergab 118 lx in der positiv polaren Bedingung und 3 lx in der negativ polaren Bedingung. Während der Korrekturleseaufgabe lasen die Teilnehmer 36 Texte, die jeweils in 10 pt Helvetica (mit einer x-Höhe von 0.25° Sehwinkel) präsentiert wurden. In Experiment 2 lasen die Teilnehmer sowohl positiv als auch negativ polar dargestellte Texte. Texte der gleichen Polarität wurden jeweils in Blöcken zu drei Texten präsentiert, sodass jeder Studienteilnehmer sechs positiv und sechs negativ polare Blöcke in einer randomisierten Reihenfolge las. Zwischen zwei Blöcken unterschiedlicher Polarität wurde ein gradueller Wechsel der Polarität über einen Zeitraum von 30 s eingefügt. Die Studienteilnehmer trugen während der Erhebung SMI Eye Tracking Glasses (SMI SensoMotoric Instruments GmbH, Teltow, Deutschland). Sie wurden darüber informiert, dass ihre Blickbewegungen und Pupillengröße aufgezeichnet wurden. Vor Beginn der Testung wurde eine 3-Punkt-Kalibrierung durchgeführt, um mit den Eye Tracking Glasses akkurate Messungen durchführen zu können.

Der Pupillendurchmesser war in der positiv polaren Bedingung signifikant kleiner als in der negativ polaren Bedingung, $t(34) = -17.49$, $p < .01$, $d_z = 2.96$ (Abbildung 1 in Piepenbrock, Mayr & Buchner, 2013). Außerdem fiel die Korrekturlesegenauigkeit in der positiv polaren Bedingung signifikant besser aus als in der negativ polaren Bedingung, $t(34) = 4.54$, $p < .01$, $d_z = 0.77$. Des Weiteren war die Lesegeschwindigkeit signifikant höher bei positiv polarer Textdarstellung als bei negativ polar dargestellten Texten, $t(34) = 4.04$, $p < .01$, $d_z = 0.68$.

Um den Beitrag des Pupillendurchmessers auf die Korrekturleseleistung der Teilnehmer spezifizieren zu können, wurde ein linear gemischtes Modell aufgestellt. Die Teilnehmer und Texte dienten als zufällige Variablen unter der Annahme gegenseitiger Unabhängigkeit und der Pupillendurchmesser (in mm) als kontinuierlicher Prädiktor der Korrekturlesegenauigkeit. Das gleiche Modell wurde für die Vorhersage der Lesegeschwindigkeit verwendet. Die Korrekturlesegenauigkeit stieg in dem Modell signifikant mit abnehmendem Pupillendurchmesser an ($b = -0.24$, $SE = 0.04$, $t = -6.04$, $p < .01$). Ebenso stieg die Lesegeschwindigkeit mit abnehmendem Pupillendurchmesser signifikant an ($b = -2.12$, $SE = 0.41$, $t = -5.12$, $p < .01$).

Auch in Experiment 2 zeigte sich der Vorteil positiver Polarität in der Korrekturlesegenauigkeit und in der Lesegeschwindigkeit. Somit konnten die Ergebnisse von Experiment 1 repliziert werden. Darüber hinaus konnte die Bildschirmluminanz-Hypothese empirisch gestützt werden. Es konnte nachgewiesen werden, dass die Pupillen der Teilnehmer im Mittel in der positiv polaren Bedingung tatsächlich einen geringeren Durchmesser aufwiesen als in der negativ polaren Bedingung. Dieser Befund komplementiert die Verhaltensdaten, die darlegen, dass die Teilnehmer positiv polar dargestellte Texte genauer und schneller lesen konnten als negativ polar dargestellte. Es ist sogar denkbar, dass der maximal mögliche Vorteil positiver Polarität in der Lesbarkeit mit der gegenwärtigen Studie unterschätzt wird. Der durchschnittliche Pupillendurchmesser der Teilnehmer betrug in der positiv polaren Bedingung 2.1 mm und lag somit unter dem von Campbell und Gubisch (1966) ermittelten Referenzwert von 2.4 mm, bei dem die Einbußen durch sphärische Aberrationen einerseits und Diffraktion anderseits minimiert sind. Es ist deshalb anzunehmen, dass bei einer etwas dunkleren positiv polaren Anzeige eine Pupillengröße im Bereich des Referenzwertes erreicht worden und die Lesbarkeit noch besser ausgefallen wäre.

Es ist allerdings zu beachten, dass Experiment 2 keine Aussagen über Kausalzusammenhänge erlaubt, da der Pupillendurchmesser in der Studie lediglich gemessen und nicht experimentell manipuliert wurde. Folglich kann der Vorteil positiver Polarität nicht eindeutig auf den verringerten Pupillendurchmesser bei positiv polarer Textpräsentation zurückgeführt werden. Betrachtet man Experiment 2 in Isolation, ist also nicht auszuschließen, dass andere Faktoren, wie zum Beispiel eine stärkere Vertrautheit mit dunkler Schrift auf hellem Hintergrund (Hall & Hanna, 2004) oder die größere Ressourcenaufwendung der Retina für die Enkodierung negativer Kontraste (das heißt bei positiver Polarität; Ratliff et al., 2010), die Leseleistung zusätzlich beeinflusst haben. Diese Variablen können allerdings nicht erklären, warum der Vorteil positiver Polarität verschwindet, wenn die Gesamthelligkeit von positiv und negativ polaren Anzeigen konstant gehalten wird (Buchner et al., 2009). Wichtig an Experiment 2 ist außerdem, dass es insofern einen strengen Test der Bildschirmluminanz-Hypothese darstellt, als diese Hypothese als widerlegt gelten müsste, wenn der Pupillendurchmesser sich nicht als Funktion der Anzeigenpolarität verändert hätte.

4. Experiment 3

In den Experimenten 1 und 2 wurden die Wirkmechanismen des Vorteils positiv polarer Textpräsentationen untersucht. In beiden Studien konnte die Bildschirmluminanz-Hypothese den gefundenen Vorteil positiver Polarität erklären. Um die Lesbarkeit digitaler Anzeigen zu optimieren, muss folglich die Darstellung dunkler Schrift auf hellem Hintergrund empfohlen werden. Diese Empfehlung kann allerdings vorerst nur für junge, normalsichtige Personen ausgesprochen werden. Denn obwohl der Vorteil positiver Polarität inzwischen ein robuster Effekt zu sein scheint, basieren die einschlägigen experimentellen Evidenzen größtenteils auf Untersuchungen junger, normalsichtiger Teilnehmer. Aufgrund altersbedingter Veränderungen im Auge ist allerdings denkbar, dass sich der Vorteil positiv polarer Textdarstellungen für ältere Personen reduziert, nicht mehr zeigt oder sogar umkehrt und damit die Darstellung heller Schrift auf dunklem Hintergrund vorteilhafter ist. Eine Untersuchung der Anzeigenpolarität im Alter scheint angesichts des demographischen Wandels in industrialisierten Gesellschaften und der wachsenden Bedeutung digitaler Anzeigen auch für ältere Personen unabdingbar. Die Analyse des Effekts der Anzeigenpolarität auf die Sehschärfe und Korrekturlesefähigkeit jüngerer und älterer Erwachsener war Gegenstand des dritten Experiments.

Im Laufe des Lebens kommt es zu verschiedenen Veränderungen im Auge. Beispielsweise führt eine altersbedingte Verengung der Pupille (senile miosis, Haegerstrom-Portnoy & Morgan, 2007), eine zunehmende Verdickung der Linse (Weale, 1989) sowie eine allmähliche Linsentrübung dazu, dass die retinale Beleuchtungsstärke im Alter erheblich abnimmt. So wird bei einer 60-jährigen Person die Retina nur noch von etwa einem Drittel des Lichts erreicht, das auf die Retina einer 20-jährigen Person trifft (Weale, 1963). Folglich sollte eine hohe Bildschirmluminanz besonders vorteilhaft für ältere Personen sein.

Die Trübungserscheinungen des alternden Auges treten allerdings nicht gleichmäßig auf. Veränderungen der Linsenproteine (Berke & Rauscher, 2007) und des Glaskörpers (Sebag, 1987) führen zu einer stärkeren unsystematischen Brechung eintreffender Lichtstrahlen, die Streulicht erzeugt. So wird in der Literatur oft berichtet, dass das vermehrte Streulicht nicht nur zu einer Reduktion des Kontrasts des retinalen Abbilds, sondern auch zu einer gesteigerten Blendempfindlichkeit im Alter führt (z.B. Berke & Rauscher, 2007; Schierz, 2011). Diese Probleme würden durch eine höhere Beleuchtung verstärkt werden, sodass eine hohe Bildschirmluminanz nicht von Vorteil, sondern sogar nachteilig für ältere Personen sein könnte. Es stellt sich nun also die Frage, ob solche nachteiligen Effekte zu einer Reduzierung, Eliminierung oder sogar Umkehr des Vorteils positiver Polarität für ältere Personen führen.

Die Erforschung des Polaritätseffekts bei sehbehinderten Personen legt nahe, dass Trübungen im okularen System tatsächlich zu besserer Leseleistung bei negativ als bei positiv polarer Textdarstellung führen können (Legge, Rubin, Pelli, & Schleske, 1985). Sloan (1977) berichtet ferner über sehbehinderte Patienten, die spezielle Geräte zum Lesen nutzen, um sich die Texte negativ polar anzeigen zu lassen. Papadopoulos und Goudiras (2005) betonen ebenfalls die Vorteile einer negativ polaren Textdarstellung für sehbehinderte Personen mit Trübungen im okularen System und empfehlen adaptive Hilfsprogramme für Computer, durch die Nutzer die Anzeigenpolarität individuell je nach Präferenz einstellen können. Einem ähnlichen Ansatz folgt man in der Produktentwicklung bei Apple. So lässt sich beispielsweise die Polarität der Bildschirmdarstellung durch einen einfach erreichbaren Menüpunkt in den Betriebssystemen Mac OS X (seit 2001) und iOS umkehren.

Westheimer, Chu, Huang, Tran und Dister (2003) untersuchten den Polaritätseffekt bei Patienten einer Augenklinik im Alter von 20 bis 88 Jahren. Den Teilnehmern wurden zur Messung der Sehschärfe Sehprobentafeln mit Snellen-Buchstaben in positiver und negativer Polarität präsentiert. Die Sehschärfe jüngerer Teilnehmer unterschied sich nicht zwischen den Polaritätsbedingungen. Mit zunehmendem Alter der Teilnehmer zeigte sich jedoch ein Vorteil negativer Polarität. Das heißt, dass ältere Studienteilnehmer eine höhere Sehschärfe bei der Darstellung weißer Buchstaben auf schwarzem Hintergrund erreichten als bei Testungen mit schwarzen Buchstaben auf weißem Hintergrund. Die Autoren führten diesen Vorteil negativ polarer Anzeigen auf intraokulare Lichtstreuung im alternden Auge zurück, die zu einer Reduzierung des Kontrasts des retinalen Abbilds besonders für positiv polare Optotypen führe (für detaillierte Ausführungen zum Verhältnis zwischen optischer Streuung, Kontrastpolarität und wahrgenommenem Kontrast, siehe Westheimer, 2001; Westheimer & Liang, 1995).

Auf Basis der Befunde bei sehbehinderten Personen und der Studie von Westheimer et al. (2003) wäre eine negativ polare Textdarstellung für ältere Personen zu empfehlen. Allerdings ist es fraglich, ob Befunde aus Untersuchungen sehbehinderter Personen ohne Weiteres auf ältere Personen generalisiert werden können. Des Weiteren weist die Studie von Westheimer et al. (2003) erhebliche methodische Mängel auf wie zum Beispiel Decken- und Reihenfolgeeffekte bei den Sehschärfemessungen. Darauf wird in der Diskussion der Ergebnisse von Experiment 3 noch genauer eingegangen.

Festzuhalten bleibt, dass die Annahme, der Vorteil positiver Polarität verringere sich im Alter, verschwände oder kehre sich sogar um, aufgrund der physiologischen Veränderungen im alternden Auge nicht von der Hand zu weisen ist. Allerdings lässt sich aufgrund der bisherigen Datenlage nicht sagen, ob dies wirklich der Fall ist. In Experiment 3 wurde daher durch eine Sehschärfebestimmung mittels Landolt C-Optotypen und durch eine Korrekturleseaufgabe getestet, ob sich ein Vorteil positiv polarer Darstellung auch bei älteren Personen zeigt. Verglichen wurden die Befunde der älteren Stichprobe mit einer Kontrollgruppe junger Erwachsener.

Ein Vorteil positiver Polarität wurde für jüngere Teilnehmer erwartet. Ein vergleichbarer Vorteil positiver Polarität für ältere Teilnehmer würde dafür sprechen, dass der Nettogewinn einer höheren Bildschirmluminanz bei älteren Personen dem Gewinn bei jüngeren Personen entspricht. Hingegen sollte der Vorteil positiver Polarität bei älteren Teilnehmern in dem Ausmaß reduziert oder sogar zu einem Nachteil umkehrt sein, in dem Einbußen durch Blendungseffekte den Vorteil der höheren Luminanz aufheben.

Teilnehmer im Alter von 60 bis 85 Jahren und im Alter von 18 bis 33 Jahren wurden randomisiert der positiv oder negativ polaren Bedingung zugeteilt. Personen mit behandlungsbedürftigen Veränderungen des Auges wie beispielsweise einer klinisch relevanten und/oder subjektiv beeinträchtigenden Katarakt wurden von der Untersuchung ausgeschlossen. Zunächst erfolgte die Messung der Sehschärfe mittels FrACT (Version 3.7.1 vom 27.10.2011; Bach, 2007), wobei die Landolt C-Ringe entweder positiv oder negativ polar dargestellt wurden. Die Luminanz betrug 350 cd/m^2 für weiße Bildschirmelemente und 1 cd/m^2 für schwarze Elemente (jeweils gemessen am Monitor ohne Berücksichtigung der Umgebungsbeleuchtung). Die Messung der Umgebungsbeleuchtung am Ort des Auges des Betrachters ergab 16 lx in der positiv polaren Bedingung und 0 lx in der negativ polaren Bedingung. Im Anschluss folgte eine Korrekturleseaufgabe, die größtenteils identisch zu Experiment 1 war mit folgenden Änderungen: Der Text-Hintergrund-Kontrast betrug c = (1 cd/m^2 - 350 cd/m^2) / (1 cd/m^2 + 350 cd/m^2) = -1 in der positiv polaren Bedingung (schwarzer Text auf weißem Hintergrund) und c = 1 in der negativ polaren Bedingung (weißer Text auf schwarzem Hintergrund). Die Messung der Umgebungsbeleuchtung ergab 117 lx in der positiv polaren Bedingung und 3 lx in der negativ polaren Bedingung. Während der Korrekturleseaufgabe lasen die Teilnehmer 28 Texte, die jeweils in 10 pt Helvetica (mit einer x-Höhe von 0.25° Sehwinkel) präsentiert wurden. Vor und nach der Korrekturleseaufgabe füllten die Teilnehmer papierbasierte Fragebögen zum subjektiven Empfinden aus. Auf die subjektive Maße und die Ergebnisses dazu wird hier nicht weiter eingegangen (vgl. dazu Piepenbrock, Mayr, Mund & Buchner, 2013).

Die gemessene Sehschärfe war für jüngere und ältere Teilnehmer in der Bedingung positiver Polarität höher als in der negativ polaren Bedingung. Der Vorteil positiver Polarität war kleiner für ältere als für jüngere Teilnehmer. Zudem waren die Sehschärfewerte der jüngeren Teilnehmer besser als die Werte der älteren Teilnehmer unabhängig von der Polaritätsbedingung (Abbildung 1 in Piepenbrock, Mayr, Mund & Buchner, 2013). Eine 2 × 2 ANOVA mit den Gruppenfaktoren Polarität und Alter zeigte statistisch signifikante Effekte der Polarität, $F(1, 163) = 69.31$, $p < .01$, $\eta^2 =$

.30, und des Alters, $F(1, 163) = 42.91$, $p < .01$, $\eta^2 = .21$. Die Interaktion zwischen den Faktoren erreichte ebenfalls statistische Signifikanz, $F(1, 163) = 19.80$, $p < .01$, $\eta^2 = .11$. Post-hoc *t*-Tests zeigten, dass der Vorteil positiver Polarität für jüngere Teilnehmer ($t(82) = 9.93$, $p < .01$, $d = 2.17$) und ältere Teilnehmer ($t(81) = 2.53$, $p = .01$, $d = 0.58$) signifikant war.

Die Korrekturlesegenauigkeit fiel für jüngere und ältere Teilnehmer in der Bedingung positiver Polarität besser aus als in der negativ polaren Bedingung. Zudem war die Korrekturlesegenauigkeit der jüngeren Teilnehmer besser als die Leistung der älteren Teilnehmer unabhängig von der Polaritätsbedingung (Abbildung 2 in Piepenbrock, Mayr, Mund & Buchner, 2013). Eine 2 × 2 A-NOVA mit den Gruppenfaktoren Polarität und Alter zeigte statistisch signifikante Effekte der Polarität, $F(1, 165) = 9.92$, $p < .01$, $\eta^2 = .06$, und des Alters, $F(1, 165) = 38.95$, $p < .01$, $\eta^2 = .19$. Die Interaktion zwischen den Faktoren erreichte keine statistische Signifikanz, $F(1, 165) = .60$, $p = .44$, $\eta^2 < .01$.

Die Lesegeschwindigkeit war vergleichbar in der positiv und der negativ polaren Bedingung sowie für jüngere und ältere Teilnehmer (Abbildung 3 in Piepenbrock, Mayr, Mund & Buchner, 2013). Eine 2 × 2 ANOVA mit den Gruppenfaktoren Polarität und Alter zeigte weder einen statistisch signifikanten Effekt der Polarität, $F(1, 165) = 0.16$, $p = .69$, $\eta^2 < .01$, noch des Alters, $F(1, 165) = 0.44$, $p = .51$, $\eta^2 < .01$. Die Interaktion zwischen den Faktoren wurde ebenfalls nicht statistisch signifikant, $F(1, 165) = 0.28$, $p = .60$, $\eta^2 < .01$.

Auch in Experiment 3 zeigte sich für jüngere Personen der erwartete Vorteil positiver Polarität. Sie erzielten eine höhere Sehschärfe und Korrekturlesegenauigkeit bei positiv als bei negativ polarer Darstellung[4]. Bei den älteren Teilnehmern zeigte sich ebenfalls ein Vorteil positiver Polarität in der Sehschärfe als auch in der Korrekturlesegenauigkeit.

Auch wenn der Vorteil positiver Polarität in den Sehschärfemessungen deutlich geringer für ältere als für jüngere Personen ausfiel (mit Effektgrößen von $d = 0.58$ bzw. $d = 2.17$), stehen die Ergebnisse von Experiment 3 im Widerspruch zu den Befunden von Westheimer et al. (2003). Die Autoren berichteten eine bessere Sehschärfe für ältere Personen bei Sehprobentafeln mit negativ als mit positiv polarer Darstellung von Snellen-Buchstaben und erklärten diese durch verstärktes intraokulares Streulicht bei hellen, positiv polaren Anzeigen. Die Interpretation dieser Studie ist allerdings aufgrund der gravierenden methodischen Mängel problematisch. Zum Beispiel zeigte sich bei der Messung der Sehschärfe ein starker Deckeneffekt, da Messungen lediglich bis zu einer Sehschärfe von 1.33 (20/15) möglich waren. Um eine akkurate Sehschärfemessung bei normalsichtigen Personen durchführen zu können, sollte allerdings eine maximale Sehschärfe von 2.0 oder höher bestimmbar sein (Bach, 2007). Zudem ist es wahrscheinlich, dass Reihenfolgeeffekte die Ergebnisse beeinflusst haben, da den Teilnehmern immer zuerst die linke, positiv polare Sehprobentafel präsentiert wurde und anschließend die rechte, negativ polare Tafel. Übungserfahrungen, die die Teilnehmer mit der positiv polaren Sehprobentafel sammelten, verbesserten möglicherweise ihre Leistung während der Sehschärfemessungen mit der negativ polaren Tafel. Diese Übungseffekte erscheinen noch wahrscheinlicher angesichts der Tatsache, dass beide Tafeln die gleiche Auswahl von Snellen-Buchstaben pro Testzeile zeigten.

Auf den ersten Blick scheinen die Ergebnisse des dritten Experiments in Konflikt mit dem bei sehbehinderten Personen beobachteten Vorteil negativer Polarität zu stehen (z.B. Legge, Rubin, et al., 1985; Sloan, 1977). Allerdings wurden Personen mit behandlungsbedürftigen Veränderungen des Auges wie beispielsweise einer klinisch relevanten und/oder subjektiv beeinträchtigenden Katarakt von der Untersuchung im Rahmen des dritten Experiments ausgeschlossen. Der Fokus der beschriebenen Studie lag auf altersbezogenen, nicht behandlungsbedürftigen Veränderungen des Auges. Es ist also durchaus denkbar, dass eine vermehrte Lichtstreuung die Lesbarkeit positiv polarer Anzeigen für ältere Personen mit behandlungsbedürftigen Veränderungen der Linse oder des Glaskörpers beeinträchtigt.

Für ältere Personen ohne klinisch relevante und/oder subjektiv beeinträchtigende Sehschwächen durch eine Katarakt oder andere Erkrankungen scheint dies allerdings eine vernachlässigbare Rolle zu spielen. Folglich wird die Präsentation dunkler Schrift auf einem hellen Hintergrund bei digitalen Anzeigen unabhängig vom Alter der Zielgruppe empfohlen.

5. Allgemeine Diskussion

In der modernen Informationsgesellschaft kommen Menschen jeden Tag mit digitalen Medien in Berührung. Die Kontexte, in denen digitale Anzeigen genutzt werden, sind dabei so vielfältig wie die Menschen, die sie verwenden (Ziefle, 2009). Daher ist es entscheidend, die Lesbarkeit dieser Anzeigen für die Bedürfnisse unterschiedlichster Nutzer zu optimieren. Zum einen ist hierbei die stetige Weiterentwicklung der zugrundeliegenden Technologien von Bedeutung, die die Voraussetzungen für eine hohe Anzeigenqualität schafft. Das Potenzial der heute verfügbaren teils hochauflösenden flimmerfreien Medien muss anschließend durch eine ergonomische Anzeigengestaltung genutzt werden. Die Faktoren, die hinsichtlich der Lesbarkeit elektronischer optischer Anzeigen optimiert werden können, umfassen unter anderem den Leuchtdichtekontrast, die Polarität, die Zeichenhöhe, die Konstanz der Textgröße, die Zeichenstrichbreite, das Verhältnis der Zeichenbreite zur Zeichenhöhe, das Zeichenformat, sowie den Zeichen-, Wort- und Zeilenabstand (DIN EN ISO 9241-303, 2011). Im Fokus der vorliegenden Arbeit stand die Anzeigenpolarität mit den Zielen, die Wirkmechanismen des Effekts der Polarität zu verstehen und Empfehlungen zur Anzeigengestaltung für Personen verschiedener Altersgruppen zu ermitteln.

Experiment 1 untersuchte das Zusammenspiel von Anzeigenpolarität und Schriftgröße. Im Konsens mit der entsprechenden Literatur zeigte sich ein Vorteil positiver Polarität in einer Korrekturleseaufgabe (Bauer & Cavonius, 1980; Buchner & Baumgartner, 2007; Chan & Lee, 2005; Mayr & Buchner, 2010; Radl, 1980; Taptagaporn & Saito, 1990, 1993; Tsang et al., 2012) sowie eine bessere Leseleistung bei größerer Schrift (Bernard et al., 2003; Fagan et al., 1986; Griffing & Franz, 1896; Luckiesh & Moss, 1939; Miyao et al., 1989; Smith, 1979). Das Hauptaugenmerk der Studie lag allerdings auf dem Befund, dass der Vorteil positiver Polarität wie erwartet mit abnehmender

Schriftgröße zunahm. Somit konnte die Bildschirmluminanz-Hypothese gestützt werden, die besagt, dass die typischerweise helleren Anzeigen bei positiv polarer Textdarstellung für den Vorteil positiver Polarität ausschlaggebend sind (Buchner et al., 2009). Es wird angenommen, dass sich die Pupille infolge der höheren Bildschirmluminanz positiv polarer Anzeigen stärker verengt und somit zu einer Reduzierung sphärischer Aberrationen und einer Erhöhung der Schärfentiefe führt (z.B. Charman & Whitefoot, 1977; Green et al., 1980; Liang & Williams, 1997; Lombardo & Lombardo, 2010; Lopez-Gil et al., 2013; Y. Wang et al., 2003). Dies ermöglicht eine bessere Detailwahrnehmung, die vor allem beim Lesen kleiner Schriften von Bedeutung ist (Smith, 1979).

Experiment 2 zielte darauf ab, die Bildschirmluminanz-Hypothese mit konkreten physiologischen Daten zu untermauern. Da der Großteil der Studien zum Polaritätseffekt auf Verhaltens- und Präferenzmaßen basierte und die Annahme der verstärkten Pupillenverengung bei positiv polaren Anzeigen weitgehend theoretisch begründet und bisher nicht erfasst worden war, wurde der Einfluss der Anzeigenpolarität auf die Pupillengröße direkt untersucht, indem der Pupillendurchmesser gemessen wurde, während die Teilnehmer positiv und negativ polar dargestellte Texte Korrektur lasen. Es zeigten sich ein verringerter Pupillendurchmesser und eine bessere Korrekturleseleistung bei positiv polarer Textdarstellung. Somit wurde die Bildschirmluminanz-Hypothese auch durch Experiment 2 unterstützt. Durch die höhere Bildschirmluminanz positiv polarer Anzeigen kommt es zu einer deutlichen Reduzierung des Pupillendurchmessers, die zu einem schärferen retinalen Abbild führt (Campbell & Gubisch, 1966) und somit eine bessere Leseleistung ermöglicht.

Aus den Experimenten 1 und 2 kann jeweils die Empfehlung abgeleitet werden, Text in Form dunkler Schrift auf einem hellen Hintergrund darzustellen. Experiment 3 testete die Gültigkeit dieser Empfehlung für ältere Personen. Angesichts altersbedingter Veränderungen im Auge und Befunden aus Untersuchungen sehbehinderter Personen war es denkbar, dass der Vorteil positiv polarer Textdarstellungen für ältere Personen verschwände oder sich sogar umkehre und die Darstellung heller Schrift auf dunklem Hintergrund vorteilhaft sei (Legge, Rubin, et al., 1985; Westheimer et al., 2003). Es zeigte sich jedoch, dass eine positive Anzeigenpolarität sowohl bei jüngeren als auch bei älteren Personen von Vorteil ist. Für die Optimierung der Lesbarkeit digitaler Anzeigen wird also die Präsentation dunkler Schrift auf einem hellen Hintergrund unabhängig vom Alter der Zielgruppe empfohlen.

Des Weiteren zeigte sich in der vorliegenden Arbeit eine bemerkenswerte Diskrepanz zwischen objektiven Performanzmaßen und den subjektiven Einschätzungen der Studienteilnehmer. So konnte der Vorteil positiver Polarität in allen Experimenten deutlich in den objektiven Leistungsmaßen nachgewiesen werden. In den subjektiven Bewertungen der Textlesbarkeit durch die Teilnehmer zeigten sich hingegen teilweise keine Unterschiede zwischen positiv und negativ polarer Textdarstellung (z.B. hinsichtlich der Fokussierbarkeit auf den Text). Diese Diskrepanz deutet möglicherweise darauf hin, dass die Nutzer nicht sensibel für die Effekte ergonomischer Anzeigengestaltung auf ihre Leistung sind. Daher ist es die Aufgabe der Designer, den Vorteil positiver Polarität bei der Gestaltung digitaler Anzeigen zu berücksichtigen.

Es ist jedoch zu beachten, dass die Empfehlung, Text in Form dunkler Schrift auf hellem Hintergrund darzustellen, in Abhängigkeit des Anwendungskontextes mit Einschränkungen verbunden ist. Es wurde dargelegt, dass positiv polare Anzeigen mehr Licht ausstrahlen als negativ polare Anzeigen. Dies kann zum Beispiel bei Nachtfahrten im Auto zu Problemen führen, da helle positiv polare Anzeigen im Autoinnenraum die Dunkeladaptation der Augen und somit die Sensitivität des Fahrers für kontrastarme Objekte auf der Straße reduzieren (Mayr & Buchner, 2010). Für gut lesbare Instrumentenanzeigen, die die Objekterkennung bei geringem Kontrast nicht beeinträchtigen, empfehlen die Autoren daher, rot statt weiß als Hintergrundfarbe der Anzeigen zu wählen. Hintergrund dieser Empfehlung ist die physiologische Reaktivität von Rezeptorzellen der menschlichen Retina: Das Maximum der spektralen Empfindlichkeit der Stäbchen, die für das Dämmerungssehen verantwortlich sind, liegt bei circa 500 nm. Dadurch sind die Stäbchen weitestgehend insensitiv für von einem typischen TFT LCD-Monitor ausgestrahltes rotes Licht, dessen Maximum sich etwa im Bereich von 610 nm befindet.

Ein weiterer Faktor, der die Generalisierbarkeit der vorgestellten Ergebnisse möglicherweise einschränkt, ist die geringe Umgebungsbeleuchtung des experimentellen Settings. Diese Bedenken können durch Studien gemindert werden, die zeigten, dass der Einfluss der Umgebungsbeleuchtung auf den Vorteil positiver Polarität (Buchner & Baumgartner, 2007) sowie auf generelle visuelle Performanz (Lin & Huang, 2006; Menozzi, Napflin, & Krueger, 1999; Tseng, Chao, Feng, & Hwang, 2010; A. H. Wang, Tseng, & Jeng, 2007) in einem Bereich von 5 lx bis 800 lx vernachlässigbar ist. Dennoch wäre es aus der Anwendungsperspektive und im Hinblick auf die ökologische Validität interessant, zu untersuchen, wie zum Beispiel helles Sonnenlicht oder wechselnde Lichtbedingungen in der Umgebung den Vorteil positiver Polarität beeinflussen.

Festzuhalten bleibt, dass die Polarität einer digitalen Anzeige einen entscheidenden Einfluss auf ihre Lesbarkeit hat und dunkle Schrift auf hellem Hintergrund zu einer besseren Leseleistung der Betrachter führt. Der Vorteil positiver Polarität findet sich sowohl bei jüngeren als auch bei älteren normalsichtigen Personen und ist maßgeblich auf die höhere Bildschirmluminanz einer positiv polaren Anzeige zurückzuführen.

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Endnoten

[1] Im Jahr 1989 besaßen 15% aller U.S. Haushalte einen Computer (U.S. Bureau of the Census, 1989).

[2] Bei den in der vorliegenden Arbeit erwähnten Kontrastdefinitionen handelt es sich jeweils um den Michelson-Kontrast. Die Michelson-Formel wurde herangezogen, da sie üblicherweise für periodische Leuchtdichteverteilungen (z.B. Schrift) am geeignetsten erachtet wird (Haase & Rassow, 2004). Für scharf begrenzte Flächen eines Objektes unterschiedlicher Leuchtdichte würde man in der Regel die Kontrastdefinition nach Weber verwenden.

[3] Die hier vorgestellte Variable „Korrekturlesegenauigkeit“ entspricht der Variable „*proofreading performance*“ in den Einzelarbeiten zu Experiment 1 und 3 sowie der Variable „*proofreading accuracy*“ in der Einzelarbeit zu Experiment 2.

[4] Im Gegensatz zu den Experimenten 1 und 2 wurde in Experiment 3 kein Vorteil positiver Polarität in der Lesegeschwindigkeit gefunden. Diese Abweichung ist vermutlich auf eine Änderung der Instruktionen zurückzuführen, die in Experiment 3 nicht explizit betonten, dass das Hauptaugenmerk der Studie auf der Lesegenauigkeit und nicht auf der Lesegeschwindigkeit lag. Durch die vergleichbare Lesegeschwindigkeit der Teilnehmer in beiden Polaritätsbedingungen bei gleichzeitigem Vorteil der positiven Bedingung in der Lesegenauigkeit kann jedoch ein Genauigkeits-Geschwindigkeits-Ausgleich ausgeschlossen werden.

Einzelarbeiten

Experiment 1:

Piepenbrock, C., Mayr, S., & Buchner, A. (in press). Positive display polarity is particularly advantageous for small character sizes - Implications for display design. *Human Factors*. doi: 10.1177/0018720813515509

Experiment 2:

Piepenbrock, C., Mayr, S., & Buchner, A. (2013). Pupil size as an explanation for the advantage of positive polarity displays (manuscript under review).

Experiment 3:

Piepenbrock, C., Mayr, S., Mund, I., & Buchner, A. (2013). Positive display polarity is advantageous for both younger and older adults. *Ergonomics*, *56*, 1116-1124. doi: 10.1080/00140139.2013.790485

Positive Display Polarity Is Particularly Advantageous for Small Character Sizes: Implications for Display Design

Cosima Piepenbrock, **Susanne Mayr**, and **Axel Buchner,**
Heinrich-Heine-Universität, Düsseldorf, Germany

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 with a proofreading task.

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

Method: Participants performed a proofreading task with black text on white background or white text on black background. Texts were presented in four 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 such displays as those of computers, automotive control and entertainment systems, and smartphones that are increasingly used for the consumption of text-based media and communication. The sizes of these displays are limited, and it is tempting to use small font sizes 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

Address correspondence to Cosima Piepenbrock, Institut für Experimentelle Psychologie, Heinrich-Heine-Universität, D-40225 Düsseldorf, Germany; e-mail: cosima.piepenbrock@hhu.de.

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INTRODUCTION

Ergonomic display design depends on various factors, such as whether text is displayed with dark characters on light background (positive polarity) or light characters on dark background (negative polarity). Several authors reported better legibility of a positive display polarity as compared with a negative one. 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, 2013), better word–nonword discrimination (Mayr & Buchner, 2010), increased visual acuity (Piepenbrock et al., 2013), 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 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 such that the 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 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, focusing on a positive polarity text presentation results in a stronger contraction of the pupil than does focusing 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 on 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 versus 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, 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, which are increasingly used for text-based media consumption (A. Smith, 2011) and text-based communication (Office of Communications, 2012). With display diagonals in smartphones of 4 to 5 in. (in smartwatches, only 1 to 2 in.), 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 (from 0.12° to 0.49°) for text messages. The character sizes were even smaller for web pages (mean *x*-height of 0.21°, 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 in either positive polarity (black text on white background) or negative polarity (white text on black background) at four character sizes (8, 10, 12, 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 were expected such that the positive polarity advantage should be larger when reading text written in small versus 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 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 last few sentences of the text (described later), skipping most of it. 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 toward the wall. The ambient illumination at the participant's eye position was less than 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-in. (1920 × 1200 pixels, 94.34 ppi) thin film transistor display of an Apple iMac computer. 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 equaled 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 equaled 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. Subpixel rendering was used for text presentation as implemented in Apple's Mac OS X. For each participant, 10 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 (0.25°), 12 pt (0.31°), and 14 pt (0.34°). Text width varied with character size from 17 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 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 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 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 with 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 with 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 posttask questionnaire assessing their subjective experiences during the proofreading task (see Table 1). Overall, the experiment took about 45 min.

TABLE 1: Results of the Posttask Questionnaire Assessment of Participants' Subjective Experiences

	Mean Rating[a]					
Item	Positive Polarity	Negative Polarity	*t*	*df*[b]	*p*	*d*
Difficulty						
Focusing on individual words	2.00	2.06	–0.61	156	.27	–0.10
Following the lines of text	1.73	1.70	0.21	156	.42	0.043
Jumping from one line of text to the next	1.47	1.65	–1.68	154	.048	–0.25
Amount on the computer screen						
Blur	1.44	2.08	–5.31	155	< .001	–0.74
Glare	1.97	1.68	2.00	157	.024	0.32
Reflections	1.30	1.24	0.62	154	.27	0.11

[a]On a scale from 1 (no difficulty; no blur, glare, or reflections) to 4 (considerable difficulty; considerable blur, glare, or reflections).
[b]Degrees of freedom vary due to data loss.

Design

For each character size, the first text was excluded from the analysis to prevent contamination of the results from possible effects of irritation caused by the new character size. Thus, 36 texts—9 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 with character size (8, 10, 12, 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 136 participants (Faul, Erdfelder, Lang, & Buchner, 2007). We collected data from 160 participants (78 in the positive polarity condition and 82 in the negative) so that the effect that could be detected was even slightly smaller than what we had planned for ($f = .14$). Significance (*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 polarity condition than in the negative 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 multivariate analysis of variance with polarity as the between-subjects variable and character size and trial as the 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, $F(1, 158) = 8.92$, $p = .003$, $\eta^2 = .053$, indicating that the positive polarity advantage increased linearly with decreasing character size. The interactions of polarity with the quadratic and cubic components of the character

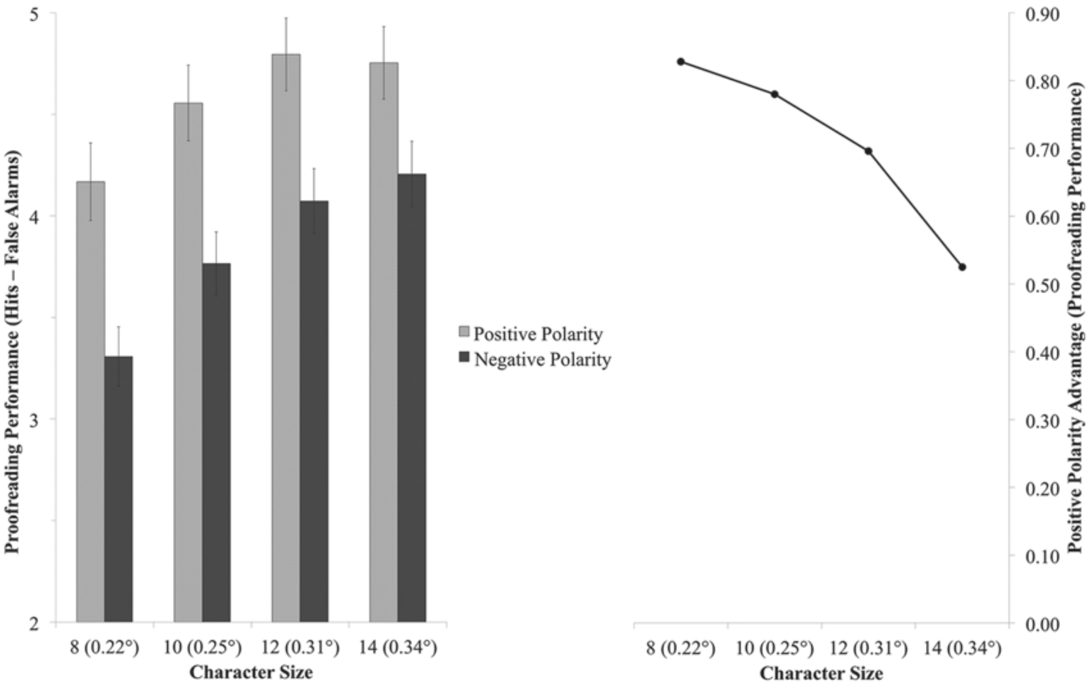

Figure 1. Left: Proofreading performance in terms of the mean number of errors detected per text adjusted by false alarms as a function of display polarity and character size in pt (visual angle of x-height). The error bars represent the standard errors of the means. Right: Difference in proofreading performance between the positive and negative polarity condition as a function of character size.

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, $p > .17$, $\eta^2 < .19$.

Reading Rate

The left panel of Figure 2 shows that reading was faster in the positive polarity condition than in the negative 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 multivariate analysis of variance with polarity as the between-subjects variable and character size and trial as the 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 interactions 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, $p > .24$, $\eta^2 < .17$.

Questionnaire Data

In the posttask questionnaire (Table 1), participants reported no significant difference between the positive and negative polarity displays in aspects of text readability (e.g., 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

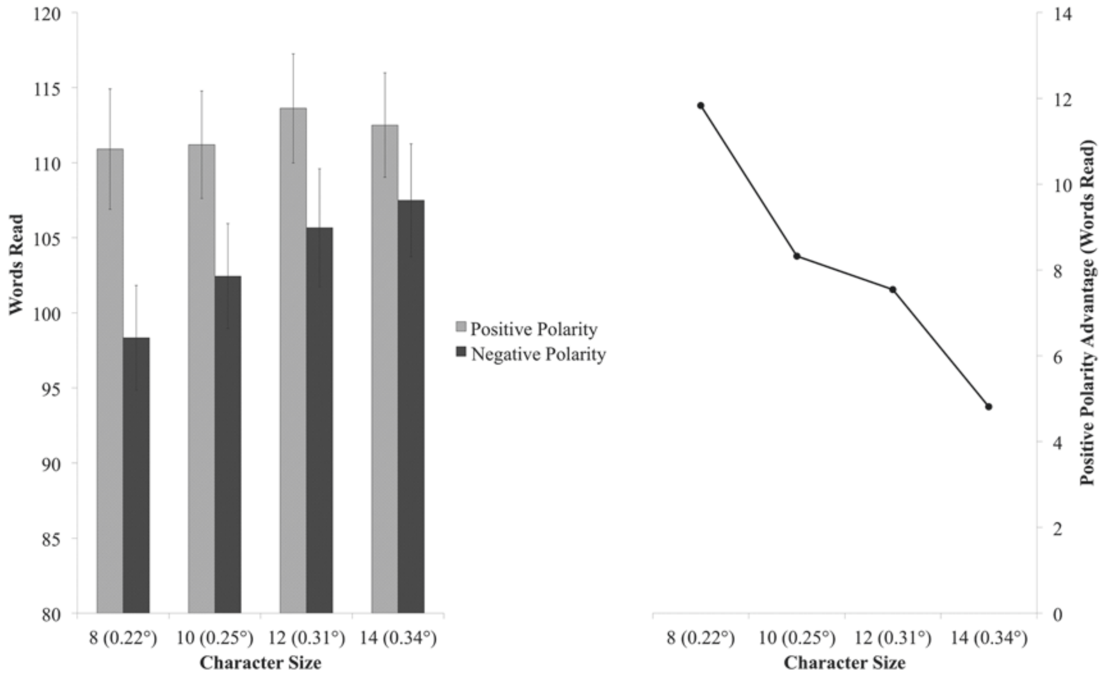

Figure 2. Left: Mean number of words read per text as a function of display polarity and character size in pt (visual angle of x-height). The error bars represent the standard errors of the means. Right: Difference in the number of words read between the positive and negative polarity condition as a function of character size.

text to the next in the negative versus the positive polarity condition. By contrast, participants reported a higher amount of glare in the positive versus the negative polarity condition.

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., 2013; 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 benefited 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 effects 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 with small characters, with *x*-heights averaging 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, not only in addition to, but also replacing, traditional analog dashboard instruments. Given that these devices will often be used during driving, reading should be facilitated as much as possible. Thus, positive polarity displays seem to be an obvious choice here. 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 thin film transistor–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 (e.g., 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 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 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 influence 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.

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KEY POINTS

- Dark characters on light background (positive polarity) lead to better proofreading performance than do 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 do light letters on dark background, particularly for small characters.

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Cosima Piepenbrock is currently affiliated with Heinrich Heine University, where she obtained her diploma in psychology in 2011.

Susanne Mayr is currently affiliated with Heinrich Heine University, where she received her venia legendi in psychology in 2011.

Axel Buchner is currently affiliated with Heinrich Heine University. He received his venia legendi in psychology at Trier University in 1998 and was appointed professor for cognitive and industrial psychology at Heinrich Heine University in 2000.

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Pupil size as an explanation for the advantage of positive polarity displays

Cosima Piepenbrock, Susanne Mayr, & Axel Buchner

Heinrich-Heine-Universität Düsseldorf

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Correspondence concerning this article should be addressed to

Cosima Piepenbrock

Institut für Experimentelle Psychologie

Heinrich-Heine-Universität

D-40225 Düsseldorf

Germany

Electronic mail: cosima.piepenbrock@hhu.de

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 support 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. A thorough understanding of the mechanisms underlying the perception of text is important for good display design. The higher brightness of positive compared to negative polarity displays leads to smaller pupils and a sharper retinal image which improves reading. Positive polarity displays are thus recommended.

Pupil size as an explanation for the advantage of positive 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 $c = (L_t\text{-}L_b)/(L_t\text{+}L_b)$ 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).

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. Importantly, if pupillary constriction is not stronger with positive polarity displays, then the display luminance hypothesis has to 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).

1.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 cd/m^2 - 328.8 cd/m^2)/(0.6 cd/m^2 + 328.8 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™ 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 more than 40 times higher in the positive than in the negative polarity condition of the proofreading task. 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. 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. Consequently, the positive polarity advantage in proofreading performance cannot be unambiguously attributed to the smaller pupil sizes with positive polarity displays. 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 might also contribute to a positive polarity advantage in reading text from TFT screens. However, these variables 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). Nevertheless it is clear that, strictly speaking, 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.

Within these limits the present study supports 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. Thus, the data also emphasises the recommendation to present text in positive polarity.

Author Notes

Correspondence should be addressed to Cosima Piepenbrock, Institut für Experimentelle Psychologie, Heinrich-Heine-Universität, 40225 Düsseldorf, Germany. E-mail: cosima.piepenbrock@hhu.de. We thank Anne-Kristin Elsner von Gronow and Christian Hoverath for their assistance with data collection. We also thank Frederik Aust for his support with data analysis.

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Footnotes

[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

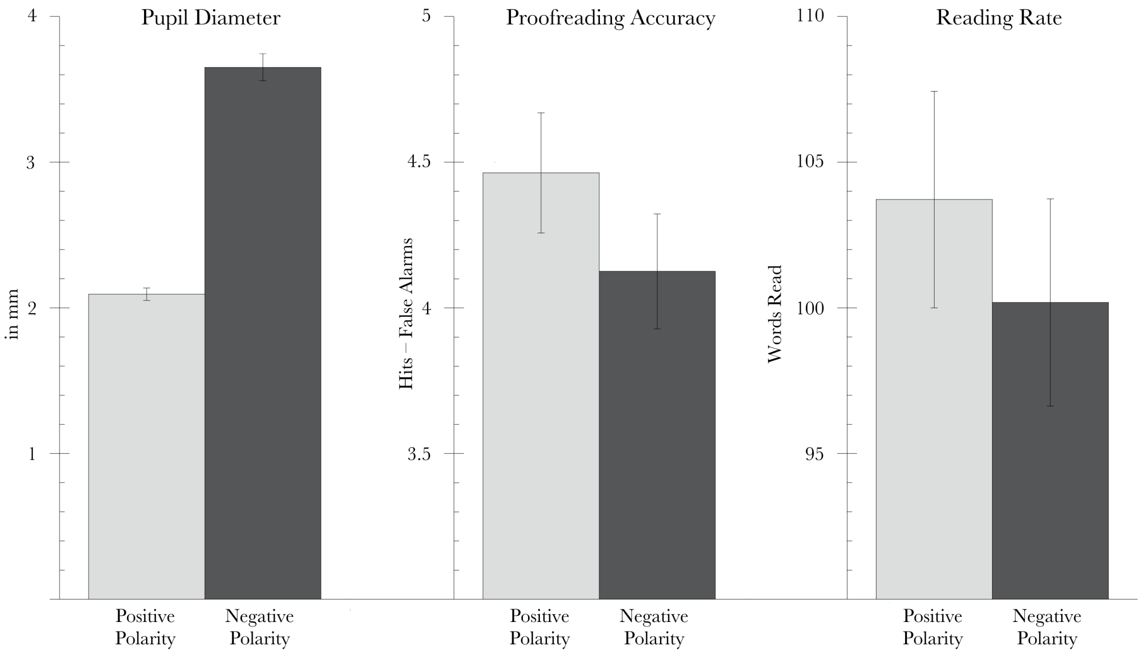
Results of the post-task questionnaire assessment of participants' subjective experiences

Item	Percentage			
	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
Positive Polarity
Negative Polarity
Proofreading Accuracy
Hits – False Alarms
5
4.5
4
3.5
Positive Polarity
Negative Polarity
Reading Rate
Words Read
110
105
100
95
Positive Polarity
Negative Polarity

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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 α 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 ($t(81) = 2.53$, $p = 0.01$, $d = 0.58$).

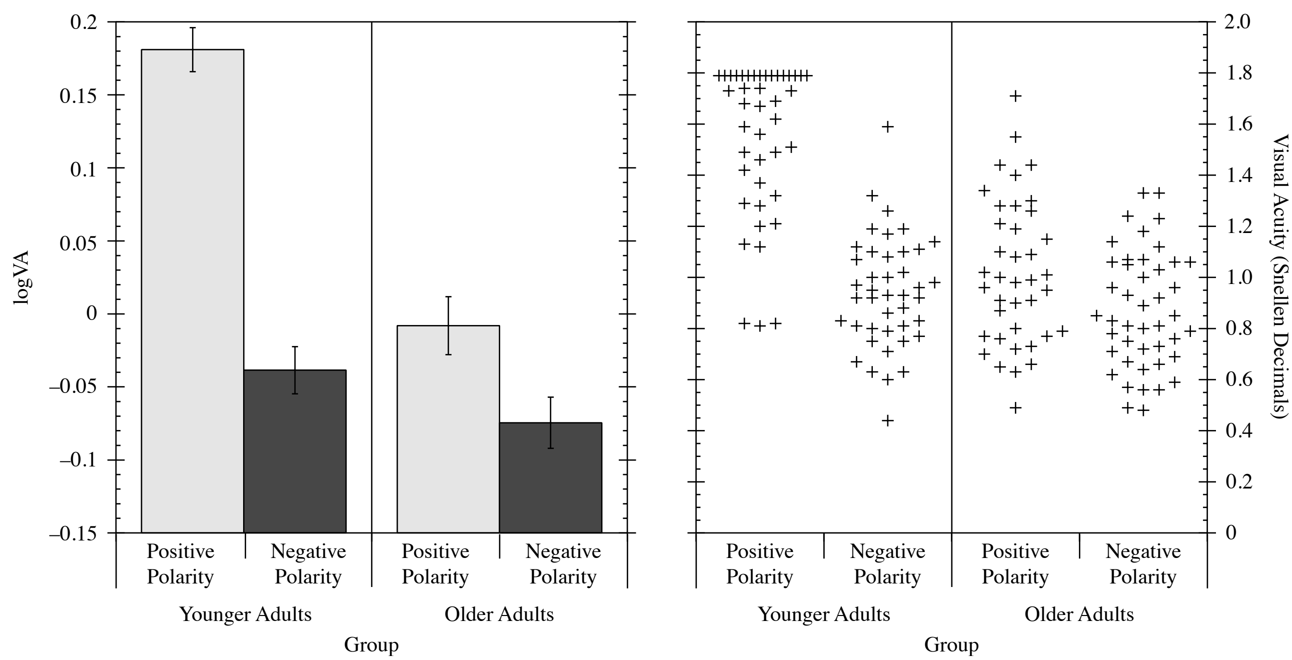

Figure 1. On the left: Mean log visual acuity (logVA) scores as a function of display polarity and age. LogVA equals log(decimal visual acuity) and -logMAR. The error bars represent the standard errors of the means. On the right: Visual acuity in Snellen decimals for the four groups. Each marker represents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

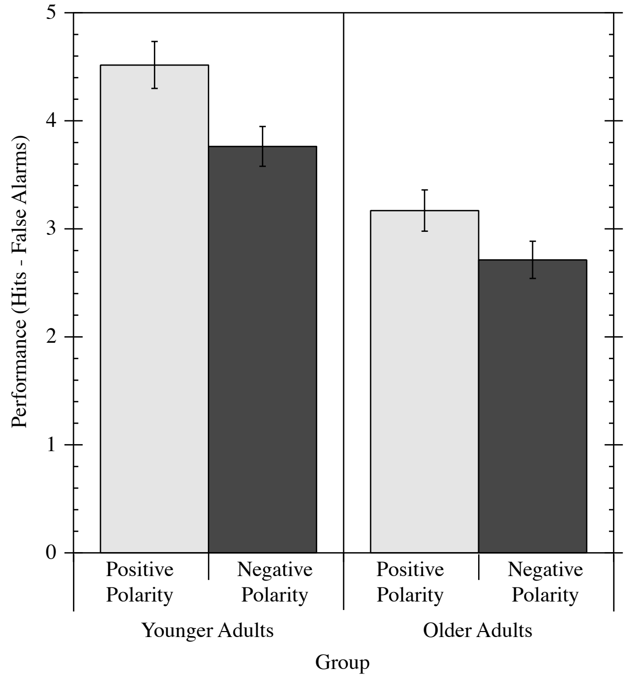

Figure 2. Mean number of errors detected per text adjusted by false alarms as a function of display polarity and age. The error bars represent the standard errors of the means.

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 2×2 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 2×2 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 α 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).

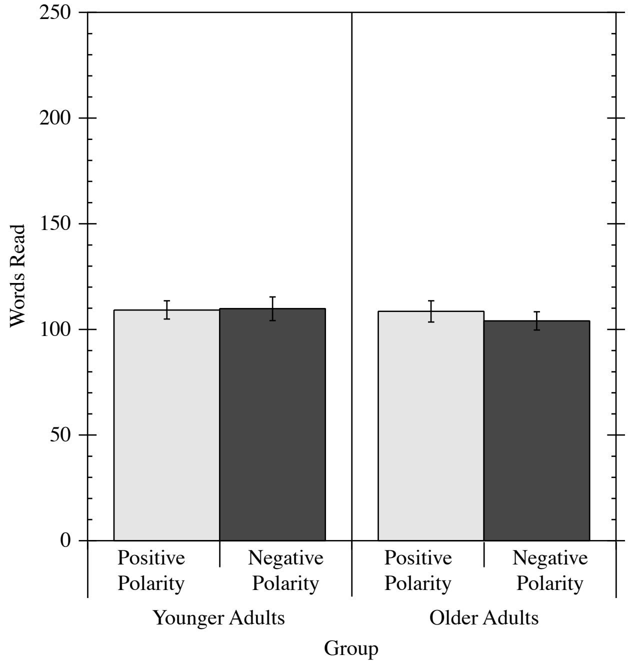

Figure 3. Mean number of words read per text as a function of display polarity and age. The error bars represent the standard errors of the means.

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.

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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_{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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