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Effects of ambient illumination, contrast polarity, and letter size on text legibility under glance-like reading

Jonathan Dobres [a,*], Nadine Chahine [b], Bryan Reimer [a]

[a] *Massachusetts Institute of Technology AgeLab and New England University Transportation Center, 77 Massachusetts Avenue, E40-209, Cambridge, MA 02139, United States*

[b] *Monotype Imaging, Inc., 600 Unicorn Park Drive, Woburn, MA 01801, United States*

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ABSTRACT

Recent research on the legibility of digital displays has demonstrated a "positive polarity advantage", in which black-on-white text configurations are more legible than their negative polarity, white-on-black counterparts. Existing research in this area suggests that the positive polarity advantage stems from the brighter illumination emitted by positive polarity displays, as opposed to the darker backgrounds of negative polarity displays. In the present study, legibility thresholds were measured under glance-like reading conditions using a lexical decision paradigm, testing two type sizes, display polarities, and ambient illuminations (near-dark and daylight-like). Results indicate that legibility thresholds, quantified as the amount of time needed to read a word accurately, were highest for the negative polarity configurations under dark ambient illumination, indicated worse performance. Conversely, the positive polarity conditions under dark ambient illumination and all conditions under bright illumination demonstrated significantly reduced thresholds, indicating greater legibility. These results are consistent with the hypothesis that the "positive polarity advantage" arises because brighter illumination produces pupillary contraction that reduces optical aberrations as light enters the eye. These results have implications for the design of automotive interfaces and other scenarios in which an interface must be optimized for glance-like reading under variations in ambient lighting conditions.

1. Introduction

Digital displays have made it easy to display text in arbitrary color and contrast combinations. In combination with advanced sensing and computing capabilities, the format of the display can be rapidly shifted based upon the intrinsic characteristics of the content, ambient conditions, or even perceived characteristics of a reader (Burke, 2006). Negative or "reverse" polarity displays—so named because they utilize light text on a dark background, as opposed to black-on-white positive polarity displays—have been in common use since the days of microfiche reading devices (Cushman, 1986) and have more recently become popular in mobile and automotive interfaces. In the automotive sector, such displays are preferred because the darker background of the negative polarity display hides wear and tear on the screen, blends in with the interior of the car, and reduces ambient illumination in the cabin during nighttime driving (i. e., positive polarity displays may emit more light in the cabin and increase glare). In some production applications, changes in the polarity of the display are made in response to ambient conditions, while other systems use a negative polarity display at all times. In the mobile device sector, negative polarity designs are less dominant, and their use appears to be more aesthetically motivated, or are used in response to the perceived optimization of the display for ambient illumination. For example, guidelines for development on the Apple Watch platform strongly encourage the use of negative polarity displays because the dark background blends in with the hardware's dark bezel. More generally, negative polarity designs popularly connote a more "high tech" aesthetic.

The relative legibility tradeoffs of negative versus positive polarity displays have garnered considerable attention in recent years. Recent research has shown that positive polarity text has superior legibility compared to negative polarity (Buchner and Baumgartner, 2007; Mayr and Buchner, 2010; Piepenbrock et al., 2013a, 2014; Piepenbrock et al., 2013b; Taptagaporn and Saito, 1990, 1993;

* Corresponding author.
E-mail addresses: jdobres@mit.edu (J. Dobres), nadine.chahine@monotype.com (N. Chahine), reimer@mit.edu (B. Reimer).

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Tsang et al., 2012). This "positive polarity advantage", as some have termed it, has been shown to increase as text size decreases (Piepenbrock et al., 2013a), and is more pronounced for younger observers (Piepenbrock et al., 2013b). Several competing theories have been put forth to explain the positive polarity advantage, which include simple familiarity effects (Hall and Hanna, 2004), a "luminance asymmetry effect", in which luminance decrements against the background are perceived as creating a greater change in luminance than increments of equal magnitude (Lu and Sperling, 2012), and the influence of spherical aberrations of the eye on visual input (Lombardo and Lombardo, 2010) Among these theories, a converging stream of evidence strongly suggests that the positive polarity advantage arises from the differing levels of illumination produced by the two display configurations (Buchner et al., 2009; Piepenbrock et al., 2014; Taptagaporn and Saito, 1990). Positive polarity displays feature a bright background and cause the pupil to contract, which in turn reduces distortions of visual input due to the aberrations of the eye. Conversely, darker negative polarity displays produce pupillary dilation, making it more likely that visual input will be affected by spherical aberrations. At least one study has demonstrated that when display illumination is held constant across polarity conditions, the positive polarity advantage is eliminated, and only the overall illumination of the display itself affects reading accuracy (Buchner et al., 2009). It should be noted, however, that this study manipulated on-screen brightness projected directly at the observer, rather than ambient illumination *per se*. While one study has shown that text polarity affects reading accuracy regardless of the available ambient illumination, this study employed a relatively narrow range of illuminations, from a near darkness of 5 lx to standard office lighting of 550 lx (Buchner and Baumgartner, 2007).

Historically, reading was performed in long stretches, as with a book or newspaper (Cushman, 1986; Judisch, 1969; Seppala, 1975). Opportunities for reading at a glance were relatively limited, and primarily involved glances to roadway signage (Ells and Dewar, 1979; Jacobs et al., 1976; Sivak et al., 1981). As a result, the bulk of legibility studies, such as those outlined above, quantify legibility using long-form reading tasks and metrics, such as proofreading and words read per minute, all of which rely on self-paced paradigms. It remains to be seen whether findings from long-form reading studies are consistent under glance-like reading scenarios, in which the observer has a limited amount of time to encode the available visual and lexical information. The increasing prominence of the smartphone and the availability of information at a glance make this a key research question in contemporary studies of legibility. Such scenarios are especially relevant in environments where information may only be available in short glances, as when using an in-vehicle interface while driving, glancing at a smartphone notification, or viewing a rapidly moving advertisement. In addition, it is unclear whether a positive or negative polarity display would "wash out" under high ambient illumination, potentially creating a pattern of results different from those observed under the relatively dim illuminations used in previous studies.

Recent research has been conducted to explicitly investigate the relative legibility of a variety of typographic factors under glance or glance-like reading conditions. A study conducted in a full cab driving simulator, in which a menu system was set in one of two possible typefaces, showed that the choice of typeface significantly impacted drivers' task completion time and number of glances to the display (Reimer et al., 2014). Later work extended these findings by showing that the same pattern of results regarding typeface could be demonstrated using a simpler desktop-based method (Dobres et al., 2016a; 2016b). While these studies show that glance legibility can be probed using empirical methods, they were all conducted under relatively dim illumination (a simulator approximating evening illumination or a dimly lit room).

Here we present a study in which legibility thresholds are measured under a glance-like reading paradigm for two contrast polarities, type sizes, and ambient lighting conditions. Legibility thresholds are operationalized as the amount of on-screen display time needed to read the stimuli with approximately 80% accuracy. This work extends earlier research by addressing limitations in the generalizability of results across variations in ambient lighting conditions. In addition, it extends the methodological underpinnings of the approach (Dobres et al., 2016b) from English to Italian. Based on previous research, we expect that legibility thresholds will be lower in the bright ambient light condition, while under the dark ambient condition, the negative polarity displays should show significantly elevated legibility thresholds compared to positive polarity displays. We also expect that legibility thresholds will be elevated at the smaller of the two text sizes. Lastly, we expect the positive polarity advantage to be more pronounced at the smaller text size.

2. Methods

2.1. Participants

The participant sample was recruited from within the Fiat Chrysler Automobiles (FCA) Italian headquarters in Torino, Italy. Participants were required to be between the ages of 20 and 65, to be in self-reported good health for their age, to drive a motor vehicle at least once per week, to have normal or corrected-to-normal vision, and to speak and read Italian as a first language. All participants provided an informed verbal consent consistent with the United States Department of Health and Human Services' "Common Rule", developed with the approval of the Massachusetts Institute of Technology's Committee on the Use of Humans as Experimental Subjects.

A total of 50 participants meeting these criteria were recruited. Of these, 1 participant withdrew due to discomfort, 5 were excluded because at least one of their estimated thresholds (see below) were in excess of 300 ms, 6 were excluded because their mean response times were greater than 1000 ms, 3 were excluded due to a probable failure to reach a stable threshold in at least one condition (defined as an absence of staircase reversals during the last 20 trials of a condition block, see below), and 1 was excluded because he/she was unable to attend all data collection sessions. This left a total of 34 participants in the analysis sample, including 13 women (mean age 36.2 years, SD 8.1) and 21 men (mean age 39.0 years, SD 9.9). There was no significant difference in age between the genders ($t(29.3) = 0.91$, $p = 0.369$).

2.2. Apparatus

The experiment utilized custom software developed by the Massachusetts Institute of Technology AgeLab, built on the PsychoPy platform (Peirce, 2008). The experiment was run on a 1.4 GHz Mac Mini under Mac OS 10.10.1 ("Yosemite"). Stimuli were displayed on a 17″ Dell 1707FPT LCD monitor with a resolution of 1280×1024 pixels and a refresh rate of 60 Hz. Participants were seated such that their eyes were approximately 0.7 m from the display. While head restraints were not used, participants were encouraged to maintain a consistent posture throughout the experiment. Participants were instructed to wear their preferred optical correction (if any) for that reading distance, and to do so throughout the experiment.