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# Effects of display curvature, display zone, and task duration on legibility and visual fatigue during visual search task

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ABSTRACT

This study examined the effects of display curvature (400, 600, 1200 mm, and flat), display zone (5 zones), and task duration (15 and 30 min) on legibility and visual fatigue. Each participant completed two 15-min visual search task sets at each curvature setting. The 600-mm and 1200-mm settings yielded better results than the flat setting in terms of legibility and perceived visual fatigue. Relative to the corresponding centre zone, the outermost zones of the 1200-mm and flat settings showed a decrease of 8%–37% in legibility, whereas those of the flat setting showed an increase of 26%–45% in perceived visual fatigue. Across curvatures, legibility decreased by 2%–8%, whereas perceived visual fatigue increased by 22% during the second task set. The two task sets induced an increase of 102% in the eye complaint score and a decrease of 0.3 Hz in the critical fusion frequency, both of which indicated an increase in visual fatigue. In summary, a curvature of around 600 mm, central display zones, and frequent breaks are recommended to improve legibility and reduce visual fatigue.



## 1. Introduction

Curved displays are currently used in various display devices (e.g., smartphones, TVs, and computer monitors). The advantages of this new display technology include a high degree of design freedom, an immersive viewing experience, screen privacy, and glare reduction (Raymond, 2013). Existing display-related ergonomics standards (e.g., AS 3590.1, AS 3590.2, ISO 9241-5, ISO 9241-303, ANSI/HFES 100, and EU 90/270/EEC) have been developed for flat and convex displays (e.g., LED and cathode-ray tube displays). However, it is largely unknown whether these standards are applicable to curved displays. Therefore, further investigation of display curvature is necessary from the ergonomic perspective, e.g., in terms of legibility and visual fatigue.

Legibility is a commonly used ergonomic criterion for display evaluation (Lin et al., 2008a, 2009; Oetjen and Ziefle, 2009; Kong et al., 2011; Lin et al., 2013; Piepenbrock et al., 2013). It depends on letter size, font type and thickness, letter and line spacing, colour contrast, viewing distance, and ambient illumination (Vartabedian, 1971; Sanders and Mccormick, 1993; Hwang et al., 1997; Bernard et al., 2003; Wickens et al., 2004; Lee and Kim, 2007; ISO 9241-303). An appropriate display curvature is likely to provide better legibility as it optically reduces image distortion (e.g., in terms of image size and shape, especially toward the lateral ends) and indirect glare. Legibility measures include reaction time and accuracy associated with finding target words in paragraphs (Hill and Scharff, 1997; Ling and Van Schaik, 2002; Ojanpää and Näsänen, 2003; Hall and Hanna, 2004; Lin et al., 2013), visual stimulus recall rate and perceptual ease (Shieh and Lin, 2000; Lin, 2003; Al-Harkan and Ramadan, 2005), and physiological correlates of legibility (Yeh et al., 2013).

Visual fatigue is another criterion that is widely used for display evaluation. Tasks involving prolonged exposure to visual displays often cause visual fatigue, which can result in headaches and task performance degradation (Sheedy, 1992a, 1992b). In general, visual fatigue can be induced either by repeated activation/deactivation of the ocular muscles (Hsu and Wang, 2013) or by prolonged accommodative response to similar focal distances (Eastman Kodak Company, 2009). Relatively similar viewing distances across a curved screen can be advantageous in the former aspect but

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disadvantageous in the latter aspect. In addition, distorted letters on the screen also increase visual fatigue (Lee, 2012), which can be mitigated by a curved screen. Visual fatigue under low cognitive workload is assessed in tasks such as reading, searching, watching, and entering data (Hwang et al., 1988; Sommerich et al., 2001; Omori et al., 2008; Kong et al., 2011; Wang et al., 2012), whereas visual fatigue primarily due to cognitive workload and visual stress is assessed in tasks such as visual discrimination, reading, computer mouse operation, and typing (Hwang et al., 1988; Sommerich et al., 2001; Omori et al., 2008; Kong et al., 2011; Wang et al., 2012). Visual fatigue is also evaluated using subjective ratings, such as the Visual Fatigue Graphic Rating Scale (VFGRS; Cushman, 1986), Eye Complaint Questionnaire (ECQ; Steenstra et al., 2009), Visual Fatigue induced by Stereoscopic Images (VFSI; Bando et al., 2012), and Visual Fatigue Scale (VFS; Benedetto et al., 2013), and physiological measures, such as critical fusion frequency (CFF; Chi and Lin, 1998; Lin et al., 2009; Bando et al., 2012; Lin and Huang, 2013; Lin et al., 2013), accommodative power (Saito et al., 1993), visual acuity, pupil diameter, ocular speed (Chi and Lin, 1998), electromyogram (EMG) of the orbicularis oculi (Nahar et al., 2011), and brain signals (Yeh et al., 2013).

Some previous studies have examined the effects of dual- or multi-monitor settings on user behaviour or performance. Grudin (2001) observed that many multi-monitor users placed primary information on the centre monitor and secondary information on the side monitors. In addition, multi-monitor users usually arrange their monitors in a curved array (Na et al., 2015). Kang and Stasko (2008) demonstrated that, compared to a 17" single monitor, a dual-monitor setting comprising two 17" monitors with an included angle of 160° has higher user preference, as it increases Internet search speed and reduces cognitive workload.

Although previous studies on display curvature have considered various tasks, display sizes, and/or display forms, the observed curvature effects are not consistent. Legibility and visual fatigue in the case of curved displays are often assessed using visual search tasks involving pseudo-texts (Wang et al., 2007, 2012; Lin et al., 2008a). Czerwinski et al. (2003) and Robertson et al. (2005) compared computer task performance on a 42" curved display and a 15" flat display, and observed faster performance, higher satisfaction, and higher preference in the case of the curved display. Wang et al. (2007) examined the effects of display curvature (0, flat; −100 mm, concave; +100 mm, convex), text/background colour combination, and ambient illuminance on task performance and user preference associated with searching for specific words printed on A4-size paper. They found that display curvature and ambient brightness did not affect task performance significantly; the flat setting was the most preferred setting, while the −100 mm (concave) setting was the least preferred setting. Using a 13 cm × 7 cm plastic mock-up display, Häkkinen et al. (2008) examined the effects of display curvature (0, ±60, and ±80 mm) and curvature direction (horizontal/vertical) on legibility. They found that neither vertically convex displays nor vertically concave displays affected legibility significantly, whereas horizontally concave displays (−60 mm and −80 mm) set parallel to the text reading direction improved legibility. Using pseudo-texts printed on A4-size paper, Lin et al. (2009) examined the effects of display curvature (0, ±100 mm), surface coating film (three types), and ambient illuminance (200, 1500, and 8000 lx) on legibility and visual fatigue, but they did not observe any significant curvature effects. Using visual stimuli printed on A4-size paper, Wang et al. (2012) studied the effects of display curvature (0, ±100 mm), age (20–29 yrs and 60–69 yrs), and ambient illuminance (50, 500, 6000, and 12,000 lx) on visual task performance. No significant display curvature effects were observed for the younger group, whereas the older group showed better performance under three treatment settings: 50 lx and +100 mm curvature, and 500 lx and flat or +100 mm curvature. Mustonen et al. (2015) found that a smaller display curvature (±50 mm) reduced visual processing speeds during a visual search task on 4.5" displays with five curvature settings (0, ±50, and ±100 mm) at a visual distance of 45 cm.

The objective of the present study is to determine ergonomic display curvatures for 50" displays by examining the effects of display curvature, display zone, and task duration on legibility and visual fatigue. Legibility was measured in terms of accuracy and speed during target searching in pseudo-texts, and visual fatigue was assessed subjectively as well as physiologically.

## 2. Methods

### 2.1. Participants

A total of 27 college students participated in the study. Their mean (SD) age was 20.9 (1.2). The participants included 14 males (mean (SD) age = 20.9 (1.2)) and 13 females (mean (SD) age = 20.9 (1.3)). The exclusion criteria were as follows: wearing a pair of glasses, being colour blind based on the Ishihara test (Ishihara and Force, 1943; Strayer and Johnston, 2001), suffering from any ocular disease in the past six months, or having visual acuity < 0.8 (=16/20 in the Snellen fractional notation) based on the Han Chun Suk test (Kee et al., 2006). The last criterion is typically used in visual performance studies (Shen et al., 2009; Wu, 2011; Schega et al., 2014). Wearing contact lenses was allowed. The mean (Snellen notation; SD) normal or corrected-to-normal visual acuities of the participants' left and right eyes were 1.1 (22/20; 0.3) and 1.0 (20/20; 0.2), respectively. All the participants provided informed consent approved by the Institutional Review Board (IRB) at Ulsan National Institute of Science and Technology (UNIST), and were compensated for their time.

### 2.2. Experimental setting and procedure

The windows of the experimental room were covered by blackout curtains to keep out sunlight and other external light. The experimental desk and the room walls were covered by black cloth to minimize their colour and reflection effects. A 50" (width × height = 1220 mm × 382 mm) experimental multi-monitor setting comprising five 244 mm × 382 mm display panels (LP171EE3, LG, Korea) was used. The size of the multi-monitor setting was similar to that of a dual-monitor setting comprising two 24" monitors (1136 mm × 438 mm). The resolution of each display panel (display zone) was 1050 × 1680 pixels. The multi-monitor curvature was adjusted to a particular setting by attaching custom brackets between the display panels. A height-adjustable chair was provided to accommodate stature variability, and a chest rest was used to facilitate neck rotation while controlling viewing distance. The horizontal viewing distance (a) to the centre display ($Z_3$; Fig. 1) was set to 500 mm. The 600-mm curvature corresponds to the sum of the horizontal viewing distance (500 mm) and the distance from the head pivot for transversal head rotation to the eye (98 mm; SAE, 2009). The horizontal field of view ($\phi$) and horizontal viewing angle ($|90° - \xi|$) varied with the display curvature (Table 1).

The presentation order of the display curvatures was determined using a 4 × 4 Latin square. Different pseudo-texts were used for each display zone as well as for each curvature setting. The visual search task was a modified version of the task described in the ISO standard (2008b). Each pseudo-text was composed of a total of 3599 alphanumeric characters (capital and non-capital letters, numerals, and spaces). The target letter "A" accounted for 2%–3% of a pseudo-text, and each text line included up to 60 letters. Spaces