Visual Performance With Small Concave and Convex Displays

Terhi Mustonen, University of Helsinki, Helsinki, Finland, **Jyrki Kimmel**, Nokia Technologies, Tampere, Finland, **Jussi Hakala**, Aalto University, Espoo, Finland, and **Jukka Häkkinen**, University of Helsinki, Helsinki, Finland

Objective: In this study, we aim to investigate how users' visual performance with a small flexible display changes based on the direction (i.e., convex, concave) and the magnitude (i.e., low, high) of the display curvature.

Background: Despite the wide interest in flexible display materials and deformable displays, the potential effects of nonplanar display surfaces on human perception and performance have received little attention. This study is the first to demonstrate how curving affects visual performance with an actual flexible display (4.5-in. active-matrix organic light-emitting diode).

Method: In a series of three experiments, we compared the performance with a planar display to the performance with concave and convex display surfaces with low and high curvature magnitudes. Two visual search tasks were employed that required the subject to detect target letters based on their contrast (Experiments 1 and 2) and identity (Experiment 3). Performance was measured as the sensitivity of target detection (d') and threshold time of the search, respectively.

Results: There were similar sensitivities for targets across the curvature variants, but the high-magnitude curvatures resulted in prolonged search times, especially for the convex form. In both of the tasks, performance was dependent on the display location, which was defined as the target's distance from the display center.

Conclusion: High curvature magnitudes should be avoided, even in small displays, because large local changes in visual stimuli decrease processing speed outside the central display.

Application: The findings have implications for the development of technologies, applications, and user interfaces for flexible displays and the design of visual display devices.

Keywords: flexible displays, handheld devices, user performance, visual search, letter identification

Address correspondence to Terhi Mustonen, Institute of Behavioural Sciences, P.O. Box 9 (Siltavuorenpenger 1 A), FIN-00014 University of Helsinki, Helsinki, Finland; e-mail: terhi.mustonen@helsinki.fi.

INTRODUCTION

The appearance and use of future display devices are not constrained by rigid display materials. Rapid advances in thin-film display technology, including the development of electrophoretic ink (E Ink) and organic light-emitting diodes (OLEDs), have already produced the flexible, paperlike displays of e-readers and mobile phones (e.g., LG G Flex, Samsung Galaxy Round). At the same time, these advances have created a base for radical changes in the designs of and interactions with future computing devices. Concepts and prototypes for bendable (Herkenrath, Karrer, & Borchers, 2008; Kildal, Paasovaara, & Aaltonen, 2012; Lahey, Girouard, Burleson, & Vertegaal, 2011; Schwesig, Poupyrev, & Mori, 2004), rollable (Pillias, Hsu, & Cubaud, 2013), foldable (Khalilbeigi, Lissermann, Kleine, & Steimle, 2012), and even self-actuated shape-changing display devices (Roudaut, Karnik, Löchtefeld, & Subramanian, 2013) have been introduced in recent years, and interaction based on the physical deformation of such devices has risen to the active focus of research (Herkenrath et al., 2008; Khalilbeigi et al., 2012; Kildal et al., 2012; Lahey et al., 2011; Lee et al., 2010; Pillias et al., 2013; Roudaut et al., 2013; Schwesig et al., 2004; Wightman, Ginn, & Vertegaal, 2011). It has been predicted that ultimately, portable display devices will contain lightweight, high-resolution, multitouch displays that can be bent, curved, rolled, or folded without damaging the display structure. These deformable displays present contents on a malleable surface that can be static (e.g., curved to a form) or changeable (e.g., curved for a certain purpose) via user-initiated or device-initiated deformation or both (Vertegaal & Poupyrev, 2008).

Despite the wide interest in flexible display materials, the potential effects of nonplanar

display surfaces on human perception and performance have received little attention. In particular, comprehensive data on visual performance with curved small displays are missing. When displayed contents are transferred from planar to nonplanar surfaces, it is crucial to understand how this change alters the observer's ability to process visual information. In this study, we investigate visual performance with curved small displays that have static display curvatures. We measure observers' performance in two visual search tasks, which are presented on a flexible active-matrix organic light-emitting diode (AMOLED) display that is bent into five configurations. We aim to compare the performance with curved display surfaces to the performance with a planar display and to clarify how the curvature's direction (i.e., concavity, convexity) and magnitude (i.e., low or high radius size) affect visual perception and the speed of processing of the displayed information. In the following subsections, we introduce characteristics that may differentiate planar and curved displays in regard to visual perception as well as discuss previous research related to curved portable displays.

Perception of Curved Displays

A curved display surface can be formed by bending the display about its vertical or horizontal axis along its short or long side. When combined with the curvature's magnitude, these bending directions generate numerous variations for concave and convex surfaces that may differ in how they affect visual perception. Although current flexible display technologies generally feature wide viewing angles and good contrast (Chen et al., 2003; Kalyani & Dhoble, 2012), bending places stress on the display materials, which may degrade the optical characteristics of the display (e.g., brightness and contrast). Such decrements are critical for portable devices that are used in various environments because ambient light alone affects display legibility (Lee, Shieh, Jeng, & Shen, 2008; Singh, Unni, Solanki, & Deepak, 2012).

In addition to optical characteristics, viewing information from a curved display differs from viewing information from a planar display due to changes in display geometry (Figure 1). First,

the orientation of a displayed object relative to the observer's eyes varies slightly based on the direction and magnitude of curvature and the object's location on the display. Second, the depth change along the display surface may result in accommodative responses of the eye. These two features may alter visual perception in a manner that, when combined with changes in the optical characteristics, leads to the deterioration of visual performance.

Local Orientation Change With Curved Displays

The retinal image of a displayed object changes with the local curvature of the display surface. Here, we describe this change as *slant*, which refers to the angle between the line of sight and the surface normal to the viewed surface (Figure 1; for review of coordinate systems, see Grossman, Wigdor, & Balakrishnan, 2007; Norman, Todd, Norman, Clayton, & McBride, 2006). When the display surface and the object slant in relation to the line of sight, the retinal image foreshortens in the direction of the slant (Figure 1). Typically, such distortions are efficiently corrected by the visual system. For instance, viewing a pictorial image from an oblique line of sight produces a similar percept to perpendicular viewing despite the differential retinal images in these two conditions (Rosinski, Mulholland, Degelman, & Farber, 1980; Vishwanath, Girshick, & Banks, 2005). This perceptual invariance requires the availability of binocular and contextual information, however, because uncorrected retinal representation dominates perception that uses monocular viewing or when lacking contextual cues about the picture-plane orientation (Rosinski et al., 1980; Vishwanath et al., 2005; Wallach & Marshall, 1986). Effective compensation also seems to be limited to slants that are less than 45° of visual angle (Vishwanath et al., 2005). Furthermore, it appears that the visual system is not sensitive to detecting small changes in local orientations. When observers were asked to judge the orientation difference between two local regions of a three-dimensional object, discrimination thresholds ranged between 4° and 10° (Norman et al., 2006).

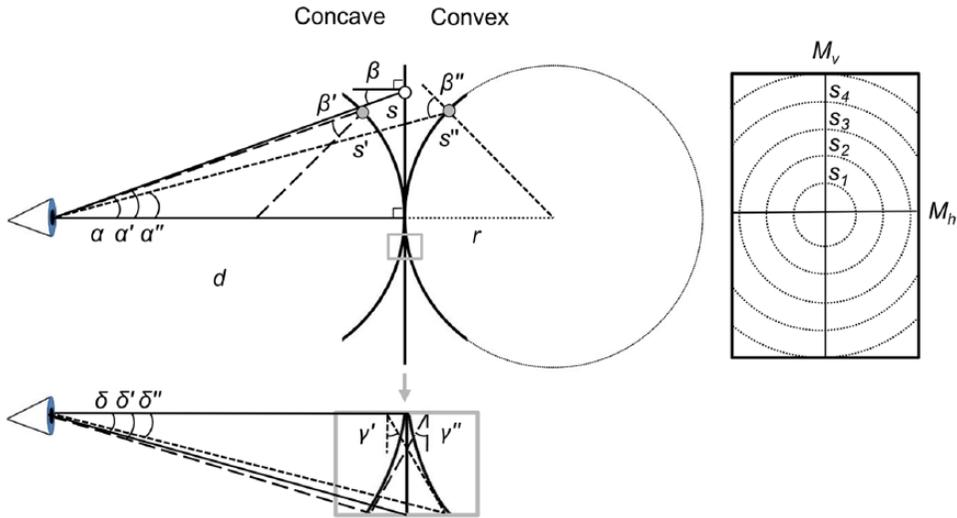Despite the amount of research that is devoted to perceptual invariance and the perception of

Figure 1. Display geometry with curved displays. Differences are shown between concave and convex displays that are curved about the horizontal axis and a planar surface from a constant viewing distance (*d*). The depth change is in the opposite direction in regard to concave (–) and convex (+) displays. Radius curvature (*r*) corresponds to the radius of a circle that best fits the curved surface, and a small *r* value, thus, indicates high curvature magnitude. The viewing angle for a given point on display surface (*β*) changes when the display is bent (*β′*, *β″*). Similarly, although an object's distance from the display center (*s*) remains the same with curved displays (*s′*, *s″*), its eccentricity (*α*) in the retinal representation decreases (*α′*, *α″*). In regard to stimuli that are presented equidistant from the center at predetermined distances (s_1, s_2, s_3, . . .), the curvature-induced eccentricity change is largest at the vertical midline of the display (M_v). In contrast, no noticeable changes occur at the horizontal midline (M_h). Local changes in surface orientation result in the slanting of objects with concave (*γ′*) and convex (*γ″*) displays. This orientation change when combined with the depth variation modifies the retinal size of the objects (*δ′*, *δ″*), when compared to the planar display (*δ*).

local orientation, only a few researchers have considered the effect of orientation change on visual performance. Larson, van Dantzich, Czerwinski, and Robertson (2000) and Grossman et al. (2007) investigated the speed of processing rotated text. Larson and colleagues measured naming speed for words that were rotated about the vertical axis, which resulted in a perspective distortion in which the letters on one end of the word were larger than the letters on the other end. They found consistent naming speed for words that were slanted up to ±55°, after which the naming speed decreased with increasing angles of rotation. Similarly, Grossman and colleagues compared recognition times for words that were rotated about the vertical or horizontal axis on a volumetric display. Their results demonstrated

that rotation about the horizontal axis had a greater effect on processing speed than rotation about the vertical axis did, but these effects only occurred after ±60° of rotation. Furthermore, performance was symmetric for rotations about the vertical axis, whereas the words that were rotated about the horizontal axis were read faster when they had positive rotation angles. In sum, previous research suggests that small local changes in displayed stimuli do not alter visual processing, but large orientation changes may affect the processing speed of displayed information.

Depth Change Within a Curved Display

When one views objects that are presented on a curved display, the distance of each object to the observer's eyes depends on its location due

to the depth change along the display surface (Figure 1). This variation may induce accommodative responses of the eye when the observer fixates on targets that are in different display locations. The accommodative responses consist of a slow component that is driven by blur in the retinal image and a fast component that is driven by binocular disparity (Campbell & Westheimer, 1960; Rashbass & Westheimer, 1961).

The retinal image of an object is sharp when the object appears at the distance to which the eye is focused. A certain extent of retinal defocus can be tolerated without the perception of blur. The range of this area is referred to as the depth of focus of the eye (DOF). DOF is roughly ±0.3 diopters under optimal viewing conditions (Campbell, 1957), and it varies depending on various internal (e.g., visual acuity, retinal eccentricity) and external (e.g., luminance, contrast; Wang & Ciuffreda, 2006) factors. Once the object falls outside the DOF, the blurred retinal image triggers the neural commands to accommodate (i.e., to minimize the blur by changing the focal power of the eye). *Accommodation* takes approximately 300 ms to initiate and approximately 1 s to reach a reasonable steady level (Campbell & Westheimer, 1960). Furthermore, within the DOF, accommodation is typically optimized slightly behind the object plane (Gambra, Sawides, Dorronsoro, & Marcos, 2009). Due to this accommodative lag, the corrective responses needed for obtaining information from curved displays may differ between concave and convex surfaces.

Another response to the depth change is *vergence*, which refers to the simultaneous rotation of the two eyes in opposite directions in order to foveate objects while maintaining fused binocular vision. The primary stimulus for vergence is the binocular disparity of the scenes that are seen by the two eyes (i.e., disparity vergence), which triggers convergent (i.e., inward) or divergent (i.e., outward) corrective movements in approximately 160 to 180 ms (Rashbass & Westheimer, 1961). Vergence can also be indirectly driven by accommodation via neural cross-links from the accommodation system (i.e., accommodative vergence), and similarly, accommodation can be driven via vergence-accommodation

cross-links (e.g., Fincham & Walton, 1957; Maxwell, Tong, & Schor, 2010, 2012). Hence, depth change in curved displays may initiate accommodation and vergence responses that aid object perception in binocular vision. Objects that are presented at different display locations act as stimuli for these responses (which take time to develop), which, in turn, affects the processing speed of the displayed information.

RESEARCH ON CURVED HANDHELD DISPLAYS

To the best of our knowledge, only a few studies concerning visual perception with small curved displays have previously been carried out. This fact may be partially due to previous low availability of hardware that has set limitations for research designs. Häkkinen, Pölönen, Salmimaa, and Hautanen (2008) took an early attempt to clarify the effect of display curvature on reading by simulating the curved text with paper prints that were attached to curved pieces of plastic. By measuring subjective reading experience with various curvature magnitudes and directions, they found that low magnitudes were preferred over high magnitudes and that concave surfaces were preferred over convex surfaces. Furthermore, displays that were curved about the horizontal axis (i.e., perpendicular to the direction of text) were associated with better reading experience than were displays that were curved about the vertical axis (i.e., to the direction of the text), which suggested that depth change adaptation was more difficult to implement along the sentences than between the lines of the text.

Wang, Tseng, and Jeng (2007) used laminated paper prints to investigate how the curvature ($r = \pm 10$ cm or planar) of electronic paper, when combined with different text background colors, affects visual performance under two illuminations. By using a task in which the subjects searched for a target word on a page of text, they found no difference in accuracy between the curvatures. The subjects preferred to perform the task with the planar surface rather than with convex or concave prints, however. Similarly, Lin, Lin, Hwang, Jeng, and Lin (2008) used laminated prints to investigate the effects of

curvature ($r = \pm10$ cm or planar), illumination, and antireflective coating on visual performance and eye strain after reading. They measured performance by using the pseudo-text search task, in which subjects search for and count the number of target letters from strings of random letters that are arranged in rows, similar to normal text (Roufs & Boschman, 1997). The results indicated that the presence of display coating (not the surface curvature) modified search performance. Interestingly, the subjects reported less visual fatigue after the pseudo-text search when curved prints were used rather than a planar surface. The results of these two studies suggest that a certain amount of the surface curvature of electronic paper can be tolerated without causing any notable effects on reading.

Pölönen, Häkkinen, Jansson, Salmimaa, and Kimmel (2008) were the first researchers to report results that were obtained with an actual flexible display. They presented short texts in a bended corner (4 cm × 5 cm) of an OLED prototype and compared (in two illuminations) reading speed and the subjective task load with two radius curvatures ($r = -20$ cm and -10 cm) to the reading speed and subjective task load that were obtained when a planar surface was used. Despite the technical constraints of the setup, the results implied that curving the display may increase the reading speed for concave ($r = -10$ cm) displays when compared to planar displays. On the other hand, the same curvature was associated with the highest subjective task load after reading, which suggested that reading from the curved surface demanded stronger commitment to the task.

To summarize, previous research with curved surfaces suggests that viewing information from curved display devices may differ from viewing information from planar displays in regard to both subjective and objective measures, and the characteristics of surface curvature seem to play an important role in visual performance. However, research on visual performance with actual curved displays is missing.

Present Study

In this study, we aimed to clarify how visual performance with small curved displays depends on the direction and magnitude of the display curvature. We measured performance with a flexible display that was bent about its horizontal axis in order to form convex and concave display surfaces with low ($r = 100$ mm) and high ($r = 50$ mm) radius curvatures. Due to the expected impact of display location on the optical characteristics and visual perception, performance was measured based on the function of stimuli's distance from the display's center point. Visual search was selected as the experimental method. Visual search has been previously utilized for various research purposes in vision science (Palmer, Verghese, & Pavel, 2000; Wolfe & Horowitz, 2004) and applied vision (e.g., Greene, Brown, & Paradis, 2013; Ojanpää & Näsänen, 2003). Because visual displays typically contain letters and other alphanumeric information, we used letters as the stimuli of the search. In Experiment 1, we validated the selected method by measuring how the contrast that is needed for target detection changes along the retinal eccentricity on a planar display. In Experiment 2, this effect was investigated with curved displays. In Experiment 3, we investigated more detailed processing of the displayed items on the concave and convex surfaces by measuring the time that was required to search and identify displayed letters.

GENERAL METHOD

Apparatus and Environment

The display was a flexible 4.5-in. (800 × 480 pixels) AMOLED display. It was viewed in five configurations: *planar* ($r = 0$ mm), *low-concave* ($r = -100$ mm), *high-concave* ($r = -50$ mm), *low-convex* ($r = 100$ mm), and *high-convex* ($r = 50$ mm) curvatures (Figure 2). The curvature was controlled by using five plastic molds that were specifically made for this purpose. The display was curved about its short side over the molds and attached to a stand in portrait orientation. Subjects viewed the display from a 45-cm distance that was perpendicular to the display center. The distance was controlled through use of a chin rest.

Figure 2. Experimental setup and display curvatures. Curvatures from left to right are *high concave* ($r =$ −50 mm), *low concave* ($r =$ −100 mm), *planar, low convex* ($r = 100$ mm), and *high convex* ($r = 50$ mm).

The display was driven as the secondary display to a computer monitor via a Display Module Controlling Unit (DMCU IV, Nokia) that converted the HDMI signal to the Video Streaming Screen Interface (ViSSI, RGB I/F). Stimulus generation and presentation was controlled by using MatLab with the Psychophysics Toolbox extension (Brainard, 1997) on a PC that used the Windows operating system. Experiments were performed in a dim room. To avoid reflections on the display, display surroundings were uniformly lit (20 cd/m²) by two vertical fluorescent lights that were front-covered with gray, nonreflective shields and positioned on both sides of the display (Figure 2). The immediate surroundings of the display were covered with gray cardboard, and the background was covered with a gray, nonreflective fabric.

Display Characterization

The display was characterized with a conoscope (Eldim VCMaster 3D Li, measurement range ±50°). The full white screen of the display in its planar state was 200 cd/m² (as measured

from the center point), with a contrast ratio (CR) of 15,000:1. The peak brightness began to be reduced at ±20°, and the brightness was only 64% of its original level at ±50° (Table 1 and Table 2). Because the black level that was measured for the CR was essentially detector noise, the measured values fluctuated. The CR at the display center indicates very high overall contrast performance, however. According to the chromaticity coordinate system of the International Commission on Illumination (CIE 1976), the coordinates for the display's white point were $u' = 0.187$, $v' = 0.461$ (Figure 3). When the display was curved, the white point drifted toward the green primary at eccentricities above approximately 5° (Table 1 and Table 2), and due to the high curvature magnitudes ($r = \pm 50$ mm), the effect was quite prominent (Figure 3). In the planar state, white point variation between the eccentricities was minor (< ±.003) due to the small change in viewing angles (< ±7°).

EXPERIMENT 1: CONTRAST-BASED TARGET DETECTION WITH A PLANAR DISPLAY

Luminance contrast is known to affect the processing speed when searching for letters (Boschman & Roufs, 1997; Ojanpää & Näsänen, 2003) and icons (Näsänen & Ojanpää, 2003) as well as in target localization (Greene et al., 2013) and reading (Legge, Rubin, & Luebker, 1987; Ojanpää & Näsänen, 2003). Typically, performance sharply improves with increasing contrast at low contrast levels and then levels off at high contrast levels (Legge et al., 1987; Näsänen & Ojanpää, 2003; Roufs & Boschman, 1997). We assumed that a task that was based on the detection of small contrast differences would also be a sensitive measure of curvature-induced changes in visual performance. Therefore, we used a letter search task in which subjects were required to detect target letters that were surrounded by other letters based on the letter–background contrast.

The aim of Experiment 1 was to clarify two methodological aspects that were of importance for the experimentation with curved displays: whether the search task was able to reveal any location-specific effects in visual processing and

TABLE 1: Local Curvature Effects in Experiment 2

Measure[a]	Planar	Concave		Convex	
		High	Low	Low	High
Minimum eccentricity (°)[b]					
1.6°		1.58	1.59	1.60	1.59
3.2°		3.03	3.14	3.19	3.11
4.8°		4.23	4.62	4.76	4.49
6.3°		5.07	5.89	6.21	5.60
6.8°		5.27	6.29	6.69	5.92
Target slant (°)					
$M \pm SEM$					
1.6°		9.44 ± 1.43	0.72 ± 0.71	4.72 ± 0.71	9.44 ± 1.43
3.2°		18.21 ± 2.83	9.10 ± 1.41	9.10 ± 1.41	18.21 ± 2.83
4.8°		36.80 ± 1.85	18.40 ± 0.93	18.40 ± 0.93	36.80 ± 1.85
6.3°		50.04	25.02	25.02	50.04
6.8°		52.86	26.43	26.43	52.86
Target height (')					
$M \pm SEM$					
1.6°	25.36	25.07 ± 0.07	25.32 ± 0.01	25.18 ± 0.04	24.79 ± 0.13
3.2°	25.33	24.24 ± 0.24	25.19 ± 0.04	24.67 ± 0.15	23.25 ± 0.45
4.8°	25.24	21.66 ± 1.37	24.79 ± 0.06	23.11 ± 0.22	18.75 ± 0.61
6.3°	25.13	18.62	24.31	21.37	14.04
6.8°	25.11	17.83	24.18	20.94	12.94
Viewing angle (°)[b]					
1.6°		15.98	8.79	5.60	12.81
3.2°		31.86	17.56	11.23	25.72
4.8°		47.53	26.27	16.89	38.81
6.3°		61.99	34.35	22.25	51.33
6.8°		66.76	37.03	24.06	55.57
Brightness (%)[b]					
1.6°	99	100	100	100	100
3.2°	99	91	99	100	96
4.8°	100	65	100	99	81
6.3°	99	n/a[c]	99	98	n/a
6.8°	99	n/a	99	97	n/a
White point deviation ($\Delta u'$; $\Delta v'$)[b]					
1.6°	−.002; .000	.000; .004	−.001; .001	.000; .000	−.003; .000
3.2°	−.001; .000	.009; .002	.006; .003	.000; .002	.001; .006
4.8°	−.001; −.001	.031; −.007	.009; .002	.002; .003	.014; −.002
6.3°	.001; .001	n/a	.015; −.001	.001; .004	n/a
6.8°	−.001; .001	n/a	.021; −.003	.003; .005	n/a

Note. High = ±50-mm radius curvature; low = ±100-mm radius curvature; n/a = not applicable.
[a]At standard eccentricities (1.6°–6.8°) defined with the planar display.
[b]Defined at display's vertical midline, where the largest changes occur.
[c]Outside the measurement range [−50°, 50°].

TABLE 2: Local Curvature Effects in Experiment 3

Measure[a]	Planar	Concave		Convex	
		High	Low	Low	High
Minimum eccentricity (°)[b]					
1.6°		1.58	1.59	1.60	1.59
5.3°		4.54	5.05	5.25	4.89
5.9°		4.87	5.56	5.83	5.33
6.6°		5.19	6.13	6.50	5.79
Target slant (°)					
M ± SEM					
1.6°		9.43 ± 1.33	4.72 ± 0.66	4.72 ± 0.66	9.43 ± 1.33
5.3°		43.75 ± 0.83	21.88 ± 0.42	21.88 ± 0.42	43.75 ± 0.83
5.9°		45.20 ± 0.58	22.60 ± 0.29	22.60 ± 0.29	45.20 ± 0.58
6.6°		51.80 ± 0.67	25.90 ± 0.33	25.90 ± 0.33	51.80 ± 0.67
Target height (')					
M ± SEM					
1.6°		16.72 ± 0.04	16.88 ± 0.01	16.79 ± 0.03	16.53 ± 0.08
5.3°		13.45 ± 0.13	16.37 ± 0.02	14.83 ± 0.07	10.92 ± 0.02
5.9°		13.23 ± 0.09	16.34 ± 0.01	14.71 ± 0.05	10.58 ± 0.14
6.6°		12.08 ± 0.12	16.15 ± 0.02	14.07 ± 0.07	8.90 ± 0.18
Viewing angle (°)[b]					
1.6°		15.98	8.79	5.60	12.81
5.3°		52.38	28.97	18.67	42.95
5.9°		58.16	32.2	20.82	47.96
6.6°		64.86	35.96	23.33	53.87
Brightness (%)[b]					
1.6°	99	100	100	100	100
5.3°	100	n/a[c]	94	99	73
5.9°	100	n/a	91	99	65
6.6°	99	n/a	85	97	n/a
White point deviation ($\Delta u'$; Δv)[b]					
1.6°	−.002; .000	.000; .004	−.001; .001	.000; .000	−.003; .000
5.3°	−.001; .000	n/a	.01; .001	.001; .004	.017; −.006
5.9°	.001; −.001	n/a	.016; −.001	.002; .003	.028; −.011
6.6°	−.001; .001	n/a	.017; −.002	.003; .003	n/a

Note. High = ±50-mm radius curvature; low = ±100-mm radius curvature; n/a = not applicable.
[a]At standard eccentricities (1.6°–6.6°) defined with the planar display.
[b]Defined at display's vertical midline, where the largest changes occur.
[c]Outside the measurement range [–50°, 50°].

whether the number of letters on the screen among which the target was to be detected would affect observers' performance. To consider the location specificity of displayed objects, we measured performance based on the function of distance from the display's center point (i.e., *eccentricity*) with a
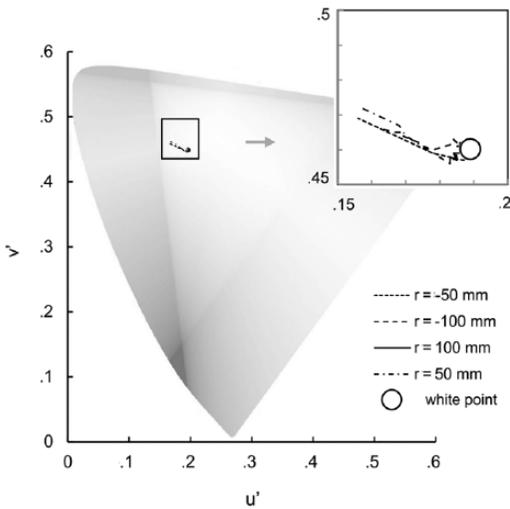
Figure 3. White point variation in curved displays (CIE 1976 coordinate). Increasing curvature magnitude and eccentricity enlarge the viewing angle, which, in turn, shifts the white point toward the green primary.

planar display. This approach also takes into account the contrast sensitivity of the human eye, which decreases from the foveal vision to the periphery (Rovamo, Virsu, & Näsänen, 1978). We assumed that with brief stimulus presentations (200 ms), the display eccentricity would correspond to the *retinal eccentricity*, and thus, stimulus letters that appeared farther away from the display center would require higher target-distracter contrast for target detection.

To consider the effect of the number of letters on the screen, we measured observers' performance with different *set sizes*. Previous research has shown that visual search that is based on simple features, such as orientation or color, is independent of set size (Palmer et al., 2000; Wolfe & Horowitz, 2004), but using contrast as the guiding attribute of search is a less studied characteristic (Wolfe & Horowitz, 2004). When visual stimuli consist of high- and low-contrast items, the high-contrast items are typically easy to detect and hard to ignore. However, when low-contrast targets are presented among high-contrast distracters, and the experimental design allows the observer to selectively attend the low-contrast targets, contrast resembles other simple features that guide the search (Pashler, Dobkins, & Huang, 2004). We reasoned that if the set size

is irrelevant in regard to performance in the contrast-based letter detection task, only one set size is needed for experimentation with curved displays.

In Experiment 1, performance was measured with the planar display at five eccentricities (1.6°–6.8°) and with four set sizes (2, 4, 8, and 12).

Method

Subjects. Three subjects (ages 33, 33, and 31 years) participated in the experiment. Two of them were authors of this paper (TM, JH), and one was naive to the purpose of the experiment. All of the subjects reported normal vision and one of them wore glasses (0/–1.25 diopters). The subjects were screened for normal near-distance visual acuity (LEA Numbers Test®), normal contrast sensitivity (Functional Acuity Contrast Test; F.A.C.T.®), and normal far-distance visual acuity with high- and low-contrast stimuli (LEA Numbers Test® at 90% and 5% contrast).

Stimuli and procedure. Stimulus characters were drawn from the set of 10 Sloan letters (*O, S, N, Z, C, H, K, R, D,* and *V*; Pelli, Robson, & Wilkins, 1988). The same letter was used for all of the characters of each trial. The character height (20 point) corresponded to 0.42°. Letters were light gray on a mid-gray (100 cd/m^2) background. The contrast [$C_{Weber} = (L_{Letters} - L_{Background}) / L_{Background}$] of the target letters varied from 18% to 78% (118–178 cd/m^2), with a step size of 12%. The contrast of the distracter letters was 90% (190 cd/m^2). The stimuli were characterized on the plane through use of a spectroradiometer (PR-670 SpectraScan).

A trial began with a light gray fixation cross (0.31°) that was shown in the center of the display for 500 ms (Figure 4). After a 200-ms delay, a set of 4 to 12 stimulus letters appeared on the circumference of an imaginary circle at one of the five eccentricities (1.6°, 3.2°, 4.8°, 6.3°, or 6.8°) for 200 ms. The distance between two adjacent letters was always at least half the eccentricity in order to avoid crowding (Bouma, 1970). Due to this requirement, set size 8 was included only for 1.6°-to-4.8° eccentricities and set size 12 for 1.6°-to-3.2° eccentricities. The subjects' task was to decide whether one of the letters (target) had a different (letter–background) contrast than the others
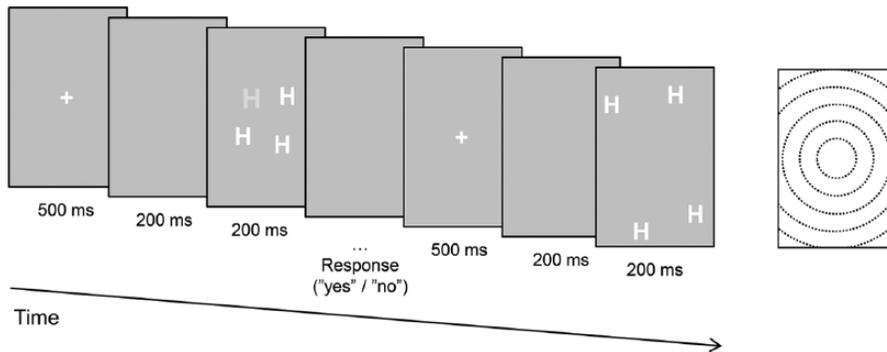
Figure 4. Contrast-based target detection task (Experiments 1 and 2). Gray sequence (left) illustrates display events during two consecutive trials. The subjects' task was to decide whether a target (i.e., letter with lower contrast) appeared among the distracters (i.e., otherwise identical letters) or not. White display (right) illustrates the eccentricities (1.6°, 3.2°, 4.8°, 6.3°, and 6.8°) at which letters were presented.

(distracters) in a two-alternative forced-choice (2AFC) procedure. The target was present in 50% of the trials. Subjects responded by pressing one of two keys on the keyboard that were marked with green ("yes") and red ("no") colors. The accuracy of answers was emphasized.

Each contrast–eccentricity combination was repeated 40 times in total. Eccentricity and target contrast varied from trial to trial in a random order. A stimulus block consisted of half the trials that were needed for a set size, and each block contained trials for one set size only. Presentation order for the blocks was counterbalanced between the subjects. Subjects were allowed to take short breaks between the blocks. Before the actual experiment, the subjects were trained on the task for 10 min. During this period, the incorrect answers were signaled with a sound mark, which was not used in the actual experiment. The experiment was divided into several sessions, with each starting with a short training period.

Analysis of results. Search performance was measured as the sensitivity of target detection with the *d*-prime (*d′*) measure of signal detection theory. *D*-prime is based on the proportions of the four response types (hit, miss, correct refusal, false alarm), and it is independent of response criteria (see Stanislaw & Todorov, 1999). The values of *d′* were calculated by using the formula $d' = z(H) - z(F)$, where H = hit rate, F = false alarm rate, and $z()$ is a probit function.

Trials with a response time over 10 s (<0.2%) were excluded from the data. The mean response time was 740 ms (SD = 381 ms).

Statistical significance of *d*-prime values was tested by using a random intercept model (linear mixed models [LMM]) that treated eccentricity (1.6°, 3.2°, 4.8°, 6.3°, 6.8°) and set size (2, 4, 8, 12) as fixed factors and subject as a random intercept. Post hoc comparisons were carried out by using the Bonferroni correction. The effect size of the full multilevel model was estimated with the reduction in mean square prediction error according to Snijders and Bosker's (1999) formula:

$$R_1^2 = 1 - \frac{\mathrm{var}(Y_{ij} - \sum_h \gamma_h X_{hij})}{\mathrm{var}(Y_{ij})}$$

$$= 1 - \frac{\hat{\sigma}^2(\mathrm{full}) + \hat{\tau}_0^2(\mathrm{full})}{\hat{\sigma}^2(\mathrm{null}) + \hat{\tau}_0^2(\mathrm{null})},$$

where Y_{ij} is the outcome variable, γ_h is the coefficient for outcome variable X_{hij} for all h variables, $\hat{\sigma}^2$ is an estimate for the variance at the first level, and τ_0^2 is an estimate of the variance at the second level.

Results and Discussion

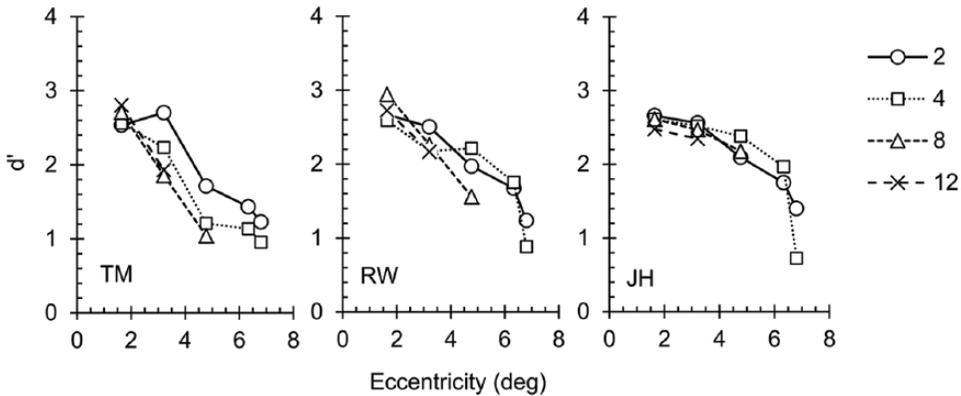The sensitivity of target detection (*d′*) with the planar display is illustrated in Figure 5.

Figure 5. Sensitivity of target detection (*d'*) with the planar display (Experiment 1). The figure plots sensitivities as a function of eccentricity (measured at 1.6°, 3.2°, 4.8°, 6.3°, and 6.8°) with four set sizes (2, 4, 8, and 12). The results for the three subjects (TM, RW, and JH) are depicted in different panels. Each data point is based on 240 trials.

Sensitivity depended on eccentricity, LMM $F(4, 28) = 46.46$, $p < .0001$, because the *d*-prime decreased when the distance from the center increased from 1.6° ($d' = 2.66$) to 3.2° ($d' = 2.31$, $p = .018$), from 3.2° to 4.8° ($d' = 1.82$, $p < .001$), and from 6.3° ($d' = 1.62$) to 6.8° ($d' = 1.07$, $p = .007$). Set size did not affect the performance, $F(3, 28) = 1.84$, $p = .164$. No Eccentricity × Set Size interaction was obtained, $F(7, 28) = 1.33$, $p = .276$. The observed effect size of the full model was $R^2 = .77$.

The fact that the contrast required for target detection strongly depended on target eccentricity demonstrates that the task was sensitive to the location-specific effects of search. This finding suggests that the contrast-based letter detection task could also be used in measuring curvature-induced performance changes at different display locations. Furthermore, because the results indicated that performance did not depend on the set size, only one set size needs to be used in the next phase of the study.

EXPERIMENT 2: CONTRAST-BASED TARGET DETECTION WITH CURVED DISPLAYS

The aim of Experiment 2 was to investigate whether the detection of displayed items depends on the direction and magnitude of the display curvature. We reasoned that by comparing target detection between the display variants

at a given eccentricity, we could demonstrate the effects of the direction and magnitude of curvature on the sensitivity and accuracy of the search. We hypothesized that performance would decrease with increasing curvature magnitude and that performance with convex displays would be inferior to performance with concave displays.

In Experiment 2, we measured search performance with two convex, two concave, and the planar display at five eccentricities (1.6°–6.8°).

Method

Subjects. The same three subjects participated as in Experiment 1.

Stimuli and procedure. The stimuli and procedure were similar to Experiment 1 (Figure 4), with the exception that only one set size was used (set size = 4). The five display configurations (planar, low concave, high concave, low convex, high convex) were tested in separate blocks. The local effects of curving at different eccentricities are shown in Table 1. A stimulus block consisted of half the trials that were needed for a curvature. Presentation order for the blocks was counterbalanced between the subjects.

Analysis of results. Search performance was measured as the sensitivity of target detection (*d'*). Additionally, the subjects' individual performance was examined based on the accuracy
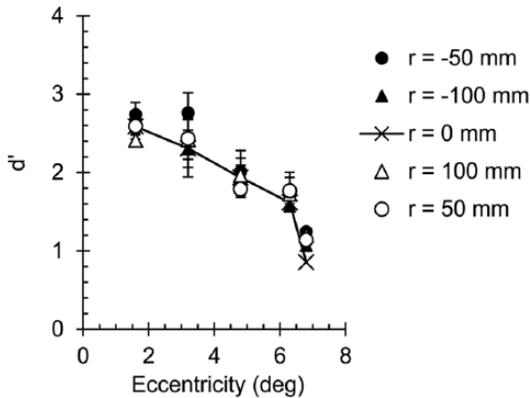
Figure 6. Sensitivity in contrast-based target detection (*d'*) with curved displays (Experiment 2). Mean (*n* = 3) results are plotted as the function of eccentricity from the display center. A solid line indicates performance with the planar display. Filled markers are concave curvatures, and open markers are convex curvatures. Error bars represent the standard errors of the mean.

data. Psychometric functions were fit to these data by using a bootstrapping procedure with 1,000 replications (Foster & Bischof, 1997). Trials with a response time over 10 s (<0.3% of the data) were excluded from the analysis of results. The mean response time was 747 ms (*SD* = 396 ms).

Statistical significance of *d*-prime values was tested by using a random intercept model (LMM) that treated eccentricity (1.6°, 3.2°, 4.8°, 6.3°, 6.8°) and curvature (high concave, low concave, planar, low convex, high convex) as fixed factors and subject as a random intercept. Post hoc comparisons were carried out by using the Bonferroni correction.

Results and Discussion

The sensitivity of target detection (*d'*) with five display configurations is illustrated in Figure 6. Contrary to our hypothesis, curvature had no significant effect on performance, LMM $F(4, 48) = 1.93$, $p = .121$, which was demonstrated by the overlapping *d*-prime values in the figure. As expected, sensitivity declined with increasing eccentricity, $F(4, 48) = 98.62$, $p < .0001$ (Figure 6); there was a significant difference in sensitivity between 3.2° and 4.8° ($p < .0001$) and between 6.3° and 6.8° ($p < .0001$). No

Curvature × Eccentricity interaction was obtained, $F(16, 48) = .72$, $p = .760$. The observed effect size of the full model was $R^2 = .77$.

To reveal individual differences in response to curved display surfaces, we observed changes in each subject's performance accuracy. Similar to the *d*-prime values, the psychometric functions that were drawn from these data demonstrated a rather small effect of curvature on target detection (Figure 7). At 1.6°-to-6.3° eccentricities, the performances follow a similar pattern of being dependent on eccentricity but demonstrating only small and inconsistent differences between the curvature variants. At 6.8°, the deviation between single observations increases, but there was still no consistent pattern that favored any of the curvatures. It appears instead that the deviation is due to the difficulty of the task at the given eccentricity, which could result from the reduced contrast sensitivity of the eye. The increased difficulty of target detection with high-eccentricity stimuli was also highlighted in the subjects' comments. In fact, based on the comments, experienced difficulty of the task was also increased by the high-magnitude curvature of the display. This notion is consistent with previous work, which suggested that the increased demands of a visual task might be seen in the subjective evaluations before they are seen in the objective performance measures (Boschman & Roufs, 1997; Pölönen et al., 2008; Wang et al., 2007).

It should be noted here that the actual eccentricities for the curved displays were somewhat smaller than the standard values that were defined with the planar display (Table 1). Due to the foreshortening of curved display area, the actual values differed from the standard by .001° to 1.53° (*M* = .35; *SD* = .44). The true variation in stimulus eccentricities was smaller, however, because no letters greater than 3.2° appeared at the midline of the display from which the minimum eccentricities were defined. Still, this between-curvatures difference was largest for stimuli that were presented at 6.8°, which may have added variation to the performance data at this distance that was close to the display edges.

Hence, the results indicated that performance in the contrast-based detection task was defined by the targets' location relative to the display
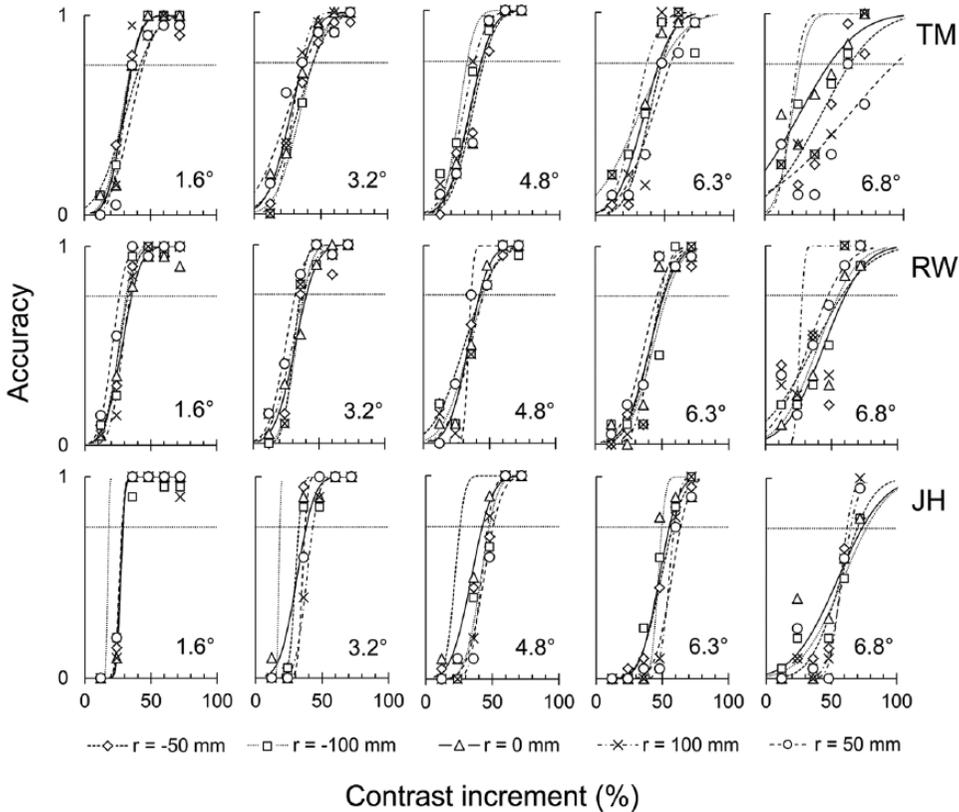
Figure 7. Accuracy of target detection with curved displays (Experiment 2). The results are plotted as the function of the target–distracter contrast for three subjects (TM, RW, JH) at five eccentricities (1.6°–6.8°), separately. Each data point is based on 20 repetitions. The horizontal line indicates a 0.75 threshold.

center rather than by the curvature of the display. The targets were detected similarly across the curvatures despite their large variation in letter slants (up to 53°; Table 1) and the foreshortening of retinal image (up to 49% of target height). Previous research has shown that perspective distortions are effectively corrected by the visual system. For instance, processing times for rotated words have been shown to remain at a constant level for up to ±60° vertical and horizontal rotation (Grossman et al., 2007; Larson et al., 2000). Consistent with these findings, our results demonstrated that displayed targets were detected similarly independent of the local curvature, which indicates that efficient compensation of retinal distortions was produced by the curved display surface. This finding suggests that under optimal viewing conditions, simple

target detection from a small (4.5-in.) curved display can maintain the level that is reached with the planar display, even when the display is bent to ±50-mm radius curvature.

A plausible reason for the small effect of curvature on performance is provided by the high native CR of the display. Despite the large variation in viewing angles between the curvature variants and in brightness reduction toward the display edges (Table 1), the 15,000:1 CR was able to reproduce the grayscale at a sufficiently steady level across the curvatures. Because the perceived contrast for a particular display location did not differ between the curvature variants, performance in the contrast-based target detection was defined by the retinal eccentricity alone. Consequently, performance with the curved displays closely resembled the performance that

was obtained with the planar display. Because the task was based on the perception of the luminance contrast, variation in the display's white point did not even alter performance (Table 1; Figure 3).

However, the contrast-based detection task that was employed in Experiment 2 did not require detailed processing of displayed information. Instead, it appears that with a large enough contrast difference, the target stood out among the otherwise identical distracters, which is similar to findings that are typically reported after using a single feature search (Palmer et al., 2000; Pashler et al., 2004; Wolfe & Horowitz, 2004). Although curving the display did not affect simple target detection, it might still affect performance in visual tasks that require a more elaborate analysis of the displayed information (Wolfe & Horowitz, 2004). Furthermore, because the lowered contrast sensitivity of the eye generally made visual processing difficult at high eccentricities, it is possible that certain between-curvature effects were covered. Performance differences outside the central display are of special importance in regard to curved displays because the local changes are largest when they are close to the display edges. These effects were further investigated in Experiment 3.

EXPERIMENT 3: THRESHOLD LETTER SEARCH TIME WITH CURVED DISPLAYS

The aims of Experiment 3 were twofold: First, we were interested in whether curving the display would affect performance in a task that required detailed visual analysis of the displayed items. Second, we wished to clarify the curvature effect for areas outside the central display. For these purposes, we employed another visual search task in which subjects searched for a target letter that was surrounded by other letters based on letter identity and measured the time that was required for a successful search (i.e., threshold search time). Because letter identity is not a preattentive feature that would facilitate target detection (Wolfe & Horowitz, 2004), the subject must serially fixate on and identify each letter on the screen in order to find the target. The time that is required for this process greatly depends on the difficulty of the task (e.g., number of distracters) and on the viewing conditions

(e.g., display curvature), which modify the fixation durations and the number of fixations that are needed for the search (Rayner, 2009). Furthermore, target processing in peripheral vision as opposed to central vision requires more eye movements and more time (Scialfa & Joffe, 1998).

Threshold search times for the five curvatures were defined at four eccentricities from the display center (1.6°, 5.3°, 5.9°, and 6.6°). The term *eccentricity* is used here for consistency, even though this measure does not necessarily correspond to retinal eccentricity in the present setup. The difficulty of the task was varied by changes in set size (8 or 12). We hypothesized that thresholds would be higher with high curvature magnitudes and with convex rather than concave displays. It was also hypothesized that threshold differences between the curvatures would increase as the eccentricity and set size increased.

Method

Subjects. Subjects were eight students and staff of Aalto University (age range = 23–33 years, mean = 27.4 years). One of them was an author of this study (TM), and the others were naive to the purpose of the experiment. All of the subjects reported normal or corrected-to-normal vision and wore their typical eye-correction equipment during the experiment. They were screened for normal visual acuity and contrast sensitivity, similar to Experiments 1 and 2. Subjects received two movie tickets or lunch vouchers as compensation for their participation.

Stimuli and procedure. Stimulus letters were again drawn from the set of 10 Sloan letters. One of the letters was the target (*H* or *R*), which remained the same during the whole experiment. The target was present in 50% of the trials, and it appeared at each letter position with an equal probability. The distracter letters were randomly selected for each trial from the set of nine remaining characters, with the restriction being that a maximum of two of the same letters was present in a trial. As characterized on the planar display, the letter height (14 point) corresponded to a 0.28° of visual angle. All of the letters were light gray (160 cd/m^2) and were on a mid-gray (100 cd/m^2) background (C$_{Weber}$ = 60%). Two set
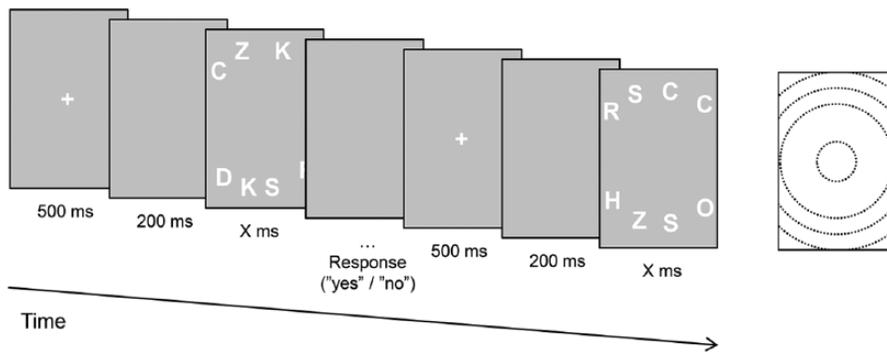
Figure 8. Letter search task (Experiment 3). The gray sequence (left) illustrates display events during two consecutive trials. The subjects' task was to decide whether a target letter (*H*) appeared among the distracter letters. The presentation duration for the stimuli varied depending on the subject's performance. The white display (right) illustrates the eccentricities (1.6°, 5.3°, 5.9°, and 6.6°) at which the letters were presented.

sizes were employed (8, 12). All of the letters for a trial were presented equidistant from the fixation cross at one of the four eccentricities (1.6°, 5.3°, 5.9°, and 6.6°; Table 2). Letter-to-letter distance was always at least 0.78°. At 6.6° eccentricity, only a set size of 8 was used.

A trial began with a fixation cross (0.31°) being presented in the center of the display for 500 ms (Figure 8). After a 200-ms delay, the stimulus letters were briefly presented on the display. The subjects' task was to decide whether the target was present or not (2AFC). They responded by pressing one of the two keys on the keyboard that were marked with green ("yes") and red ("no") colors.

The duration of the stimulus presentation was varied through the use of an adaptive staircase algorithm (Wetherill & Levitt, 1965; cf. Näsänen & Ojanpää, 2003; Ojanpää & Näsänen, 2003). In the beginning of each block, the presentation duration was 1,000 ms. After an incorrect response, the duration of the next stimulus presentation was increased by a factor of 1.26. Conversely, after three consecutive correct responses, the duration of the next stimulus presentation was decreased by the same factor. This staircase procedure was continued until the eighth reversal on the staircase. A threshold estimate that indicated a 79% probability of the subject choosing a correct answer was defined as the average of these reversals. The first five trials were not taken into account in this threshold estimate.

The experiment consisted of 10 blocks, each of which contained trials for only one set size and curvature. Within a block, the trials for each eccentricity were presented consecutively in a random order. The order of the blocks was counterbalanced between the subjects. Subjects practiced the task for 10 min before starting the actual experiment.

Analysis of results. Threshold search times were defined for five display curvatures, at four eccentricities, and with two set sizes. The average number of trials that was needed for a threshold estimate was 44 (*SD* = 12) and 41 (*SD* = 11) for set sizes of 8 and 12, respectively. Statistical significance of the estimates was tested through use of the LMM by treating curvature (high concave, low concave, plane, low convex, high convex), eccentricity (1.6°, 5.3°, 5.9°, 6.6°), and set size (8, 12) as fixed factors and subject as a random intercept. Post hoc comparisons were carried out by using the Bonferroni correction.

Results and Discussion

Threshold search times are plotted in Figure 9. Consistent with our hypotheses, the LMM indicated significant main effects of curvature, $F(4, 238) = 7.61$, $p < .0001$; eccentricity, $F(3, 238) = 60.33$, $p < .0001$; and set size, $F(1, 238) = 41.16$, $p < .0001$. The observed effect size of the full model was $R^2 = .34$. Thresholds were higher for the high curvatures ($r = \pm 50$ mm) than the low
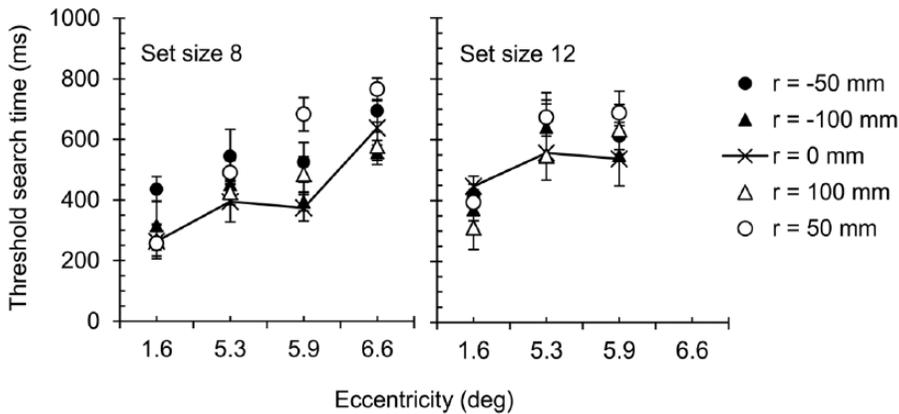
Figure 9. Threshold search times with curved displays (Experiment 3). Mean (*n* = 8) results are plotted as the function of eccentricity for two set sizes, separately. Solid lines indicate the thresholds for the planar display. Filled markers indicate concave displays, and open markers indicate convex displays. Error bars represent the standard errors of the mean.

curvatures (*r* = ±100 mm; *p* < .01), whereas performance with the low curvatures and the planar display did not differ (*p* > .05). The prolonged search times were consistent with the subjects' comments regarding the difficulty of the task. Thresholds were also higher for targets that were presented at intermediate eccentricities (5.3°–5.9°) than for targets that were near the display center (1.6°; *p* < .001), and the highest thresholds were obtained near the display edges (6.6°; *p* = .002). As expected, set size 12 resulted in longer threshold search times than set size 8.

A significant Curvature × Eccentricity interaction was also found, *F*(12, 238) = 2.21, *p* = .012 (Figure 10). Close to the display center (1.6°), threshold durations for convex displays were slightly shorter than thresholds for planar and concave displays. As the distance from the display center increased, performance with all of the curved displays decreased in relation to performance with the planar display, however. With convex displays, this performance drop peaked at approximately 6°, which indicated that the convex displays had 100-ms (for low convex) to 230-ms (for high convex) higher thresholds than the planar display at that distance. With concave displays, the relative change was smoother, with there being a 70-ms (for low concave) to 130-ms (for high concave) relative increase at peak thresholds of approximately 5°. These findings

indicate that performance with convex displays and with a high-convex curvature, in particular, was more dependent on the display location than performance with the concave counterparts was. In fact, average thresholds with the high-convex curvature varied from 320 ms to 730 ms (>400 ms), depending on eccentricity, whereas the variance with the low-convex curvature (300 ms) and both concave curvatures (250 ms) was smaller.

Moreover, Figure 10 suggests that performance with the curved displays improved relative to performance with the planar display for eccentricities beyond the 5° to 6°. This change was due to a performance drop in the planar display rather than to actual improvement in the curved displays because search speed with the planar display also slowed down beyond 6° (Figure 9). It appears that the demands of the task were generally increased at areas that were close to the display edges, which resulted in prolonged threshold durations with all of the display variants.

Whereas Experiment 2 indicated no difference in target detection between the curvature variants, Experiment 3 demonstrated that search speed for the displayed targets was clearly reduced with high curvature magnitudes. This finding reflects the different requirements of the visual tasks that were employed in the experiments. Interestingly, the constant performance
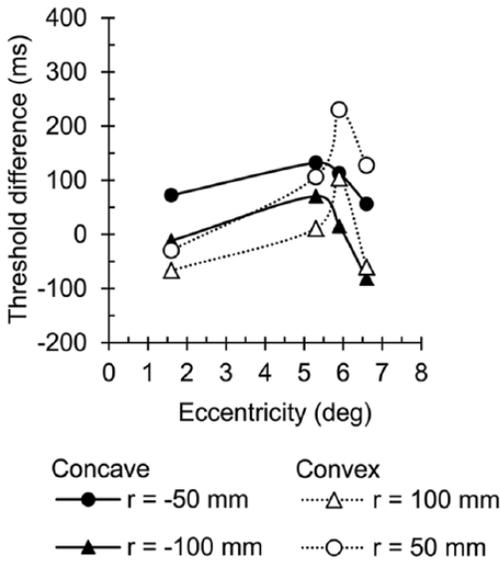
Figure 10. Effect of display curvature on threshold search times (Experiment 3). Performance with concave and convex displays relative to the planar display ($D_{Curved} - D_{Plane}$) is illustrated as the function of eccentricity. The figure combines the data for the set sizes 8 and 12 illustrated in Figure 9. Performance at the zero level corresponds to performance for the planar display. High positive values demonstrate large decrements. The results are calculated over the two set sizes. Filled markers indicate concave curvatures, and open markers indicate convex curvatures. Note that performance with low convex and low concave curvatures did not differ from the performance for the planar display.

across the curvatures in the contrast-based target detection (Experiment 2) suggests that prolonged-threshold letter search times that were associated with the high curvature magnitudes (Experiment 3) were not due to changes in contrast. The reduced performance must, therefore, result from other optical characteristics and local changes in stimulus features (Table 2).

Both brightness and the white point underwent a notable change when the display was bent to high-radius curvatures. Although the perceived contrast of the display was not affected, these changes likely interacted with other local changes in the displayed stimuli. The letters on the high curvatures were slanted over 50° at their highest slant. Although this large amount of

perspective change can be corrected by the vision system without there being a notable effect on the observer's performance (Grossman et al., 2007; Larson et al., 2000; Rosinski et al., 1980; Vishwanath et al., 2005), the resulting foreshortening in stimulus size may have slowed down the speed of search in the present case. The size reduction from the central display (1.6°) to near the display edges (6.6°) was approximately 28% with high-concave curvatures and 46% with high-convex curvatures. The corresponding values for the low-concave and low-convex curvatures (both with up to 25° letter slants) were 4% and 16%, respectively (Table 2). The larger variation in character height would also explain why performance with convex curvatures depended more on eccentricity than performance with the concave curvatures did.

Furthermore, the depth change that was associated with curved surfaces may have affected performance for the high-convex and high-concave displays. Although the stimuli were always presented with one eccentricity at a time, the depth change between characters that were simultaneously shown on the display was largest with the high curvature magnitudes. The depth change, in turn, may have triggered accommodation and vergence responses of the eye that take time to develop and stabilize (Campbell & Westheimer, 1960; Fincham & Walton, 1957; Rashbass & Westheimer, 1961). The effect of such adaptive responses is evident on tasks that measure the speed of processing visual details.

GENERAL DISCUSSION

The effect of display curvature on visual performance depended on the type of visual task. In the contrast-based target detection task (Experiments 1 and 2), the direction and magnitude of curvature did not affect performance (when compared to the planar display). In the search task that required more elaborate processing of displayed items in order to identify the targets (Experiment 3), performance was clearly reduced with high radius curvatures ($r = \pm50$ mm), especially in regard to the convex form. In both tasks, performance strongly depended on the distance from the display center at which the displayed items appeared. In particular, performance beyond 6° eccentricity severely declined.

Target Detection and Speed of Search With Curved Displays

In Experiment 2, the displayed targets were detected similarly across the curvatures. The sensitivity and accuracy of contrast-based target detection were determined by the eccentricity of the displayed items rather than by the direction or magnitude of the curvature. The eccentricity effect was an expected finding because the contrast sensitivity of the eye is known to decrease with retinal eccentricity (Cannon, 1985; Rovamo et al., 1978). However, the fact that the effect was of a similar magnitude to the planar display as to all of the curvatures suggests that curving the display had no influence on the retinal contrast reduction. The results can be interpreted in light of interplay between the display's optical characteristics and the nature of the task. The high native contrast and wide viewing angles of the display enabled detection of small contrast differences, even when the display was bent to a small curvature radius. Because the contrast was similarly perceived across the curvatures, performance in the contrast-based detection task depended only on the eccentricity of stimuli. This finding indicates that contrast acted as the single guiding feature of search in the task (cf. Pashler et al., 2004; Wolfe & Horowitz, 2004). In contrast, local changes in other optical characteristics (e.g., brightness, white point) or stimulus features (e.g., character height) that occurred when the display was curved did not play a role in the subjects' performance on the task. One should keep in mind, however, that the visual tasks that were employed here required only processing of grayscale (not color-coded) information. Still, because contrast is a key determinant of legibility with visual display units (Boschman & Roufs, 1997; Ojanpää & Näsänen, 2003), the result suggests that curving a display does not easily disrupt the detection of displayed items under optimal viewing conditions.

However, the prolonged processing times that were associated with the high curvature magnitudes ($r = \pm 50$ mm) in Experiment 3 indicated that processing visual details becomes more laborious with curved displays. The processing times were further increased by adding to the number of to-be-processed items that was on the display.

Because the perceived contrast of the stimuli did not differ between the curvatures (Experiment 2), the increased demands most likely did not result from poor legibility of the letters. Instead, the prolonged threshold durations could reflect the amount of local changes in visual stimuli with which observers must cope while performing the task. For instance, at 6.6° eccentricity, the high curvature magnitudes resulted in an average change of 53° for the viewing angle and in an average 37% reduction in letter height. The corresponding values with low curvature magnitudes ($r = \pm 100$ mm) were 23° for the viewing angle and 9% for the letter height.

Because the thresholds for the low-radius curvatures did not differ from the planar display, it appears that a notable amount of changes was tolerated by the visual system before the processing speed of the displayed items was slowed down. This finding is consistent with previous research related to visual performance with curved surfaces. Wang et al. (2007) and Lin et al. (2008) found that ±100-mm-radius curvature had no influence on visual performance with simulated electronic paper. Similarly, results by Grossman et al. (2007) and Larson et al. (2000) demonstrated that rotations of displayed text have negligible effects up to a ±55°-to-60° change (after this, performance declines sharply). When combined with the present results, these findings suggest that low curvature ratios do not alter visual performance with small displays in optimal viewing conditions. However, curvature magnitudes at a radius size of approximately 50 mm already cause a noticeable decrease in the speed of visual processing. Such decrements are particularly evident with convex display surfaces.

Limitations and Future Directions

Certain aspects must be considered in regard to the generalization of the present results. First, because we aimed to investigate baseline visual performance with curved displays without there being intervening environmental factors, the experiments were conducted in dim indoor lighting. The applicability of the results for other lighting conditions is, therefore, limited. This is particularly true in regard to bright outdoor lighting because the current flexible

technologies still encounter problems regarding sunlight readability. With emissive OLED displays, performance is limited due to the metal electrodes in the display structure. These electrodes have high reflectance, which reduces the display contrast under strong external light (Singh et al., 2012; Yang et al., 2005). Reflective technologies that are used in electronic paper utilize ambient light as the light source rather than a display backlight, and performance with such displays should, therefore, improve with an increasing intensity of light. There are always surface reflections on electronic paper, however, and excess illumination can cause additional side effects, such as glares, that further impair the ambient contrast (e.g., He, Torrance, Sillion, & Greenberg, 1991; Lin et al., 2008).

The illumination effects are further complicated by the curved display surface. Generally, the main advantage of concave displays is the reduced number of surface reflections on the display that curve toward the viewer's eyes (Figure 1). This benefit, which enhances optical characteristics, is lost or even reversed with convex displays because the light scatters away from the outward-curved surface. The lowering of visual performance that is associated with convex displays is, therefore, likely to be intensified by high illumination levels. Despite the higher vulnerability in ambient light, convex displays are still important in display design because convex surfaces are well suited in certain display applications, such as wearable electronics (Co & Pashenkov, 2008; Vertegaal & Poupyrev, 2008). Further investigation is needed in order to reveal how the characteristics of ambient light would modify performance on different types of visual tasks that are performed with curved displays.

Second, future research should clarify how visual processing with curved displays is influenced by the displayed contents. The visual stimuli in the present study consisted of single legible letters that were presented at a noticeable distance from each other. Still, increasing the set size of the displayed items from 8 to 12 significantly decreased the observers' performance on the identification task. This finding suggests that with high-density information, the degradation would be more severe. Furthermore, the spatial frequency content of the displayed information affects the accommodation response of the eye (Okada et al., 2006). With high-frequency content, changes in retinal blur are easily detected, which triggers corrective actions by the vergence-accommodation system. With low-frequency content, the blur is more difficult to detect, and corrective actions do not occur. Because the accommodative corrections take time to develop (Campbell & Westheimer, 1960; Fincham & Walton, 1957), the frequency content can greatly modify the processing speed of information with curved displays in which the depth change between display locations generates retinal blur. In addition to resulting from the high density of displayed information, the effect can result from the high spatial resolution of the display.

CONCLUSIONS AND IMPLICATIONS

When compared to conventional planar displays, even the static nonplanar displays allow for a greater degree of freedom in device design (Vertegaal & Poypyrev, 2008). Curved display surfaces enable display integration on everyday objects and wearable electronics, and eventually, complete devices will be deformable. Moreover, deformable materials enable novel interaction techniques that are based on the physical deformation of the display. In a large amount of research in recent years, authors have reported concepts in which the user communicates through use of the shape itself by bending, curving, or folding the display (e.g., Herkenrath et al., 2008; Khalilbeigi et al., 2012; Kildal et al., 2012; Lahey et al., 2011; Lee et al., 2010; Pillias et al., 2013; Roudaut et al., 2013; Schwesig et al., 2004). Therefore, deformable display materials are likely to have a great effect on the future of human-computer interaction.

As device concepts approach real products and technology matures, understanding the advantages and limitations of such concepts from the perspective of human perception and performance becomes increasingly important. The present study provides a baseline for visual performance with deformable displays by demonstrating how the direction and magnitude of static curvature affect visual search with small displays under optimal viewing conditions. By

showing that observers' performance was independent of curvature in simple detection tasks and with low-radius curvatures ($r = \pm100$ mm), we demonstrate that the visual system compensates for a large degree of the changes that are caused by curving in high-quality displays. With high curvature magnitudes ($r = \pm50$ mm), the identification of displayed items clearly decreased in speed, however. This finding was particularly true of the convex curvature, with which the speed of processing strongly depended on the display location. Because the curvature effects are supposed to be intensified by high-intensity light, using such high-magnitude curvatures in portable devices should be avoided. Furthermore, critical information should not be presented near the display edges because both sensitivity and the speed of search were reduced in locations that were beyond 5° to 6° from the display center. Finally, designers of future display applications should consider that visual performance with curved displays depends on the characteristics of the display and environment as well as the current visual task. Visual performance and ergonomics with curved display surfaces should remain an active focus of research as long as visual processing is the primary information channel in display applications.

ACKNOWLEDGMENTS

KEY POINTS

- Viewing a curved display differs from viewing a planar display due to changes in display optics and geometry, viewing angle, and accommodative responses of the eye. These changes can affect visual perception and performance.
- We compared visual performance with a flexible display in a planar and four curved configurations. The curved displays differed with respect to the direction (i.e., concave, convex) and magnitude (i.e., low, high) of curvature.
- The direction or magnitude of curvature did not change users' sensitivity for target detection in a simple target detection task. However, the speed of target identification slowed down significantly when the task was presented on a display with high curvature magnitude, particularly for the convex form.
- The findings suggest that high-magnitude curvatures cause large local changes in visual stimuli that decrease the speed of visual processing. Such decrements are particularly critical for portable devices because the ambient light of changing environments further challenges the legibility of the displayed details. Therefore, high curvature magnitudes should be avoided.

REFERENCES

Boschman, M. C., & Roufs, J. A. J. (1997). Text quality metrics for visual display units: II. An experimental survey. *Displays*, *18*, 45–64. doi:10.1016/S0141-9382(97)00004-8

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*, 177–178.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.

Campbell, F. W. (1957). The depth of field of the human eye. *Optica Acta: International Journal of Optics*, *4*, 157–164. doi:10.1080/713826091

Campbell, F. W., & Westheimer, G. (1960). Dynamics of accommodation responses of the human eye. *Journal of Physiology*, *151*, 285–295.

Cannon, M. W., Jr. (1985). Perceived contrast in the fovea and periphery. *Journal of the Optical Society of America*, *2*, 1760–1768. doi:10.1364/JOSAA.2.001760

Chen, Y., Au, J., Kazlas, P., Ritenour, A., Gates, H., & McCreary, M. (2003). Flexible active-matrix electronic ink display. *Nature*, *423*, 136. doi:10.1038/423136a

Co, E., & Pashenkov, N. (2008). Emerging display technologies for organic user interfaces. *Communications of the ACM*, *51*(6), 45–47. doi:10.1145/1349026.1349036

Fincham, E. F., & Walton, J. (1957). The reciprocal actions of accommodation and convergence. *Journal of Physiology*, *137*, 488–508.

Foster, D. H., & Bischof, W. F. (1997). Bootstrap estimates of the statistical accuracy of thresholds obtained from psychometric functions. *Spatial Vision*, *11*, 135–139.

Gambra, E., Sawides, L., Dorronsoro, C., & Marcos, S. (2009). Accommodative lag and fluctuations when optical aberrations are manipulated. *Journal of Vision*, *9*(6), 1–15.

Greene, H. H., Brown, J. M., & Paradis, B. A. (2013). Luminance contrast and the visual span during visual target localization. *Displays*, *34*, 27–32. doi:10.1016/j.displa.2012.11.005

Grossman, T., Wigdor, D., & Balakrishnan, R. (2007). Exploring and reducing the effects of orientation on text readability in volumetric displays. In M. B. Rosson & D. J. Gilmore (Eds.), *CHI '07 Proceedings of the SIGCHI Conference on Human*

Factors in Computing Systems (pp. 483–492). New York, NY: ACM. doi:10.1145/1240624.1240702

Häkkinen, J., Pölönen, M., Salmimaa, M., & Hautanen, J. (2008). Reading experience with curved hand-held displays. *Journal of the Society for Information Display*, *16*, 1099–1103. doi:10.1889/JSID16.11.1099

He, X. D., Torrance, K. E., Sillion, F. X., & Greenberg, D. P. (1991). A comprehensive physical model for light reflection. *ACM SIGGRAPH Computer Graphics*, *25*, 175–186. doi:10.1145/127719.122738

Herkenrath, G., Karrer, T., & Borchers, J. (2008). TWEND: Twisting and bending as new interaction gesture in mobile devices. In M. Czerwinski, A. M. Lund, & D. S. Tan (Eds.), *CHI '08 Extended Abstracts on Human Factors in Computing Systems* (pp. 3819–3824). New York, NY: ACM. doi:10.1145/1358628.1358936

Kalyani, N. T., & Dhoble, S. J. (2012). Organic light emitting diodes: Energy saving lighting technology. A review. *Renewable and Sustainable Energy Reviews*, *16*, 2696–2723. doi:10.1016/j.rser.2012.02.021

Khalilbeigi, M., Lissermann, R., Kleine, W., & Steimle, J. (2012). FoldMe: Interacting with double-sided foldable displays. In R. Vertegaal, S. N. Spencer, Y. Fernaeus, A. Girouard, & S. Jordà (Eds.), *TEI '12 Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction* (pp. 33–40). New York, NY: ACM. doi:10.1145/2148131.2148142

Kildal, J., Paasovaara, S., & Aaltonen, V. (2012). Kinetic device: Designing interactions with a deformable mobile interface. In J. A. Konstan, E. H. Chi, & K. Höök (Eds.), *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (pp. 1871–1876). New York, NY: ACM. doi:10.1145/2212776.2223721

Lahey, B., Girouard, A., Burleson, W., & Vertegaal, R. (2011). PaperPhone: Understanding the use of bend gestures in mobile devices with flexible electronic paper displays. In D. S. Tan, S. Amershi, B. Begole, W. A. Kellogg, & M. Tungare (Eds.), *CHI '11 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1303–1312). New York, NY: ACM. doi:10.1145/1978942.1979136

Larson, K., van Dantzich, M., Czerwinski, M., & Robertson, G. (2000). Text in 3D: Some legibility results. In T. Turner, G. Szwillus, M. Czerwinski, F. Peterno, & S. Pemberton (Eds.), *CHI '00 Extended Abstracts on Human Factors in Computing Systems* (pp. 145–146). New York, NY: ACM. doi:10.1145/633292.633374

Lee, D.-S., Shieh, K.-K., Jeng, S.-C., & Shen, I.-H. (2008). Effect of character size and lighting on legibility of electronic papers. *Displays*, *29*, 10–17. doi:10.1016/j.displa.2007.06.007

Lee, S.-S., Kim, S., Jin, B., Choi, E., Kim, B., Jia, X., Kim, D., & Lee, K. (2010). How users manipulate deformable displays as input devices. In E. D. Mynatt, D. Schoner, G. Fitzpatrick, S. E. Hudson, W. K. Edwards, & T. Rodden (Eds.), *CHI '10 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 1647–1656). New York, NY: ACM. doi:10.1145/1753326.1753572

Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading: V. The role of contrast in normal vision. *Vision Research*, *27*, 1165–1177. doi:10.1016/0042-6989(87)90028-9

Lin, Y.-T., Lin, P.-H., Hwang, S.-L., Jeng, S.-C., & Lin, Y.-R. (2008). Ergonomic evaluation of electronic paper: Influences of anti-reflection surface treatment, illumination, and curvature on legibility and visual fatigue. *Journal of the Society for Information Display*, *16*(1), 91–99. doi:10.1889/1.2835042

Maxwell, J., Tong, J., & Schor, C. M. (2010). The first and second order dynamics of accommodative convergence and disparity convergence. *Vision Research*, *50*, 1728–1739. doi:10.1016/j.visres.2010.05.029

Maxwell, J., Tong, J., & Schor, C. M. (2012). Short-term adaptation of accommodation, accommodative vergence and disparity vergence facility. *Vision Research*, *62*, 93–101. doi:10.1016/j.visres.2012.03.013

Näsänen, R., & Ojanpää, H. (2003). Effect of image contrast and sharpness on visual search for computer icons. *Displays*, *24*, 137–144. doi:10.1016/j.displa.2003.09.003

Norman, J. F., Todd, J. T., Norman, H. F., Clayton, A. M., & McBride, T. R. (2006). Visual discrimination of local surface structure: Slant, tilt, and curvedness. *Vision Research*, *46*, 1057–1069. doi:10.1016/j.visres.2005.09.034

Ojanpää, H., & Näsänen, R. (2003). Effects of luminance and colour contrast on the search of information on display devices. *Displays*, *24*, 167–178. doi:10.1016/j.displa.2004.01.003

Okada, Y., Ukai, K., Wolffson, J. S., Gilmartin, B., Iijimati, A., & Bando, T. (2006). Target spatial frequency determines the response to conflicting defocus- and convergence-driven accommodative stimuli. *Vision Research*, *46*, 475–484. doi:10.1016/j.visres.2005.07.014

Palmer, J., Verghese, P., & Pavel, M. (2000). The psychophysics of visual search. *Vision Research*, *40*, 1227–1268. doi:10.1016/S0042-6989(99)00244-8

Pashler, H., Dobkins, K., & Huang, L. (2004). Is contrast just another feature for visual selective attention? *Vision Research*, *44*, 1403–1410. doi:10.1016/j.visres.2003.11.025

Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences*, *2*, 187–199.

Pillias, C., Hsu, S, & Cubaud, P. (2013). Reading with a digital roll. In W. E. Mackay, S. A. Brewster, & S. Bødker (Eds.), *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (pp. 1377–1382). New York, NY: ACM. doi:10.1145/2468356.2468602

Pölönen, M., Häkkinen, J., Jansson, D., Salmimaa, M., & Kimmel, J. (2008). P-38: Flexible displays. Cognitive performance studies. *SID Symposium Digest of Technical Papers*, *39*, 1320–1323. doi:10.1889/1.3069386

Rashbass, C., & Westheimer, G. (1961). Disjunctive eye movements. *Journal of Physiology*, *159*, 339–360.

Rayner, K. (2009). Eye movements and attention in reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, *62*, 1457–1506. doi:10.1080/17470210902816461

Rosinski, R. R., Mulholland, T., Degelman, D., & Farber, J. (1980). Picture perception: An analysis of visual compensation. *Perception and Psychophysics*, *28*, 521–526. doi:10.3758/BF03198820

Roudaut, A., Karnik, A., Löchtefeld, M., & Subramanian, S. (2013). Morphees: Toward high "shape resolution" in self-actuated flexible mobile devices. In W. E. Mackay, S. A. Brewster, & S. Bødker (Eds.), *CHI '13 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 593–602). New York, NY: ACM. doi:10.1145/2470654.2470738

Roufs, J. A. J., & Boschman, M. C. (1997). Text quality metrics for visual display units: I. Methodological aspects. *Displays*, *18*, 37–43.

Rovamo, J., Virsu, V., & Näsänen, R. (1978). Cortical magnification factor predicts the photopic contrast sensitivity of peripheral vision. *Nature*, *271*, 54–56. doi:10.1038/271054a0

Schwesig, C., Poupyrev, I., & Mori, E. (2004). Gummi: A bendable computer. In E. Dykstra-Erickson & M. Tscheligi (Eds.), *CHI '04 Proceedings of the SIGCHI Conference on Human Factors*

in Computing Systems (pp. 263–270). New York, NY: ACM. doi:10.1145/985692.985726

Scialfa, C. T., & Joffe, K. M. (1998). Response times and eye movements in feature and conjunction search as a function of target eccentricity. *Perception and Psychophysics*, *60*, 1067–1082. doi:10.3758/BF03211940

Singh, R., Unni, N. K. N., Solanki, A, & Deepak (2012). Improving the contrast ratio of OLED displays: An analysis of various techniques. *Optical Materials*, *34*, 716–723. doi:10.1016/j.optmat.2011.10.005

Snijders, T., & Bosker, R. (1999). *Multilevel analysis*. Thousand Oaks, CA: Sage.

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, and Computers*, *31*, 137–149. doi:10.3758/BF03207704

Vertegaal, R., & Poupyrev, I. (2008). Organic user interfaces. *Communications of the ACM*, *51*(6), 26–30. doi:10.1145/1349026.1349033

Vishwanath, D., Girshick, A. R., & Banks, M. S. (2005). Why pictures look right when viewed from the wrong place. *Nature Neuroscience*, *8*, 1401–1409. doi:10.1038/nn1553

Wallach, H., & Marshall, F. J. (1986). Shape constancy in pictorial representation. *Perception and Psycholphysics*, *39*, 233–235. doi:10.3758/BF03204929

Wang, A.-H., Tseng, C.-C., & Jeng, S.-C. (2007). Effects of bending curvature and text/background color-combinations of e-paper on subjects' visual performance and subjective preferences under various ambient illuminance conditions. *Displays*, *28*, 161–166. doi:10.1016/j.displa.2007.06.003

Wang, B., & Ciuffreda, K. J. (2006). Depth-of-focus of the human eye: Theory and clinical implications. *Survey of Ophthalmology*, *51*(1), 75–85. doi:10.1016/j.survophthal.2005.11.003

Wetherill, G. B., & Levitt, H. (1965). Sequential estimation of points on a psychometric function. *British Journal of Mathematical and Statistical Psychology*, *18*, 1–10. doi:10.1111/j.2044-8317.1965.tb00689.x

Wightman, D., Ginn, T., & Vertegaal, R. (2011). BendFlip: Examining input techniques for electronic book readers with flexible form factors. In P. Compos, N. Nunes, N. Graham, J. Jorge, & P. Palanque (Eds.), *INTERACT'11 Proceedings of the 13th IFIP TC 13 International Conference on Human–Computer Interaction* (Vol. Part 3, pp. 117–133). Berlin, Germany: Springer-Verlag.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Review Neuroscience*, *5*, 1–7. doi:10.1038/nrn141

Yang, C.-J., Lin, C.-L., Wu, C.-C., Yeh, Y.-H., Cheng, C.-C., Kuo, Y.-H., & Chen, T.-H. (2005). High-contrast top-emitting organic light-emitting devices for active-matrix displays. *Applied Physics Letters*, *87*, 143507. doi:10.1063/1.2081137

Terhi Mustonen is a doctoral student in the Institute of Behavioural Sciences at the University of Helsinki. She obtained her MA in psychology from University of Helsinki in 2004.

Jyrki Kimmel is a Distinguished Researcher at Nokia Technologies in Tampere, Finland. He obtained his DSc (Tech.) degree from Tampere University of Technology in 2012.

Jussi Hakala is a doctoral student in the Department of Media Technology at Aalto University, where he obtained his master's degree in media technology in 2010.

Jukka Häkkinen is a principal investigator at Institute of Behavioural Sciences, University of Helsinki. He obtained his PhD in psychology from University of Helsinki in 2007.