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1 Visual performance with small concave and convex displays

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1 Abstract

2 **Objective:** This study aims to investigate how users' visual performance with a small flexible
3 display changes based on the direction (i.e., convex, concave) and the magnitude (i.e., low,
4 high) of the display curvature.

5 **Background:** Despite the wide interest in flexible display materials and deformable displays,
6 the potential effects of non-planar display surfaces on human perception and performance
7 have received little attention. This study is the first to demonstrate how curving affects visual
8 performance with an actual flexible display (4.5" AMOLED).

9 **Method:** In a series of three experiments, we compared the performance with a planar display
10 to the performance with concave and convex display surfaces with low and high curvature
11 magnitudes. Two visual search tasks were employed that required the subject to detect target
12 letters based on their contrast (Experiments 1 and 2) and identity (Experiment 3).

13 Performance was measured as the sensitivity of target detection (d') and threshold time of the
14 search, respectively.

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

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

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

23 **Keywords:** Flexible displays, handheld devices, user performance, visual search, letter
24 identification

1 **Précis:** The paper introduces a series of three visual search experiments to investigate how
2 the direction and magnitude of display curvature affect users' visual performance with an
3 actual flexible display.

4 Visual performance with small concave and convex displays

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

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

Perception of Curved Displays

15 A curved display surface can be formed by bending the display about its vertical or
16 horizontal axis along its short or long side. When combined with the curvature's magnitude,
17 these bending directions generate numerous variations for concave and convex surfaces that
18 may differ in how they affect visual perception. Although current flexible display
19 technologies generally feature wide viewing angles and good contrast (Chen et al., 2003;
20 Kalyani & Dhoble, 2012), bending places stress on the display materials, which may degrade
21 the optical characteristics of the display (e.g., brightness and contrast). Such decrements are
22 critical for portable devices that are used in various environments because ambient light alone
23 affects display legibility (Lee, Shieh, Jeng, & Shen, 2008; Singh, Unni, Solanki, & Deepak,
24 2012).

1 In addition to optical characteristics, viewing information from a curved display
2 differs from viewing information from a planar display due to changes in display geometry
3 (Fig. 1). First, the orientation of a displayed object relative to the observer's eyes varies
4 slightly based on the direction and magnitude of curvature and the object's location on the
5 display. Second, the depth change along the display surface may result in accommodative
6 responses of the eye. These two features may alter visual perception in a manner that, when
7 combined with changes in the optical characteristics, leads to the deterioration of visual
8 performance.

Local Orientation Change with Curved Displays

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

1 orientation difference between two local regions of a three-dimensional object, discrimination
2 thresholds range between 4° and 10° (Norman et al., 2006).

3 *Figure 1*

4 Despite the amount of research that is devoted to perceptual invariance and the
5 perception of local orientation, only a few studies have considered the effect of orientation
6 change on visual performance. Larson et al. (2000) and Grossman et al. (2007) both
7 investigated the speed of processing rotated text. Larson and colleagues measured naming
8 speed for words that were rotated about the vertical axis, which resulted in a perspective
9 distortion in which the letters on one end of the word were larger than the letters on the other
10 end. They found consistent naming speed for words that were slanted up to $\pm 55^\circ$, after which
11 the naming speed decreased with increasing angles of rotation. Similarly, Grossman and
12 colleagues compared recognition times for words that were rotated about the vertical or
13 horizontal axis on a volumetric display. Their results demonstrated that rotation about the
14 horizontal axis had a greater effect on processing speed than rotation about the vertical axis
15 did, but these effects only occurred after $\pm 60^\circ$ of rotation. Furthermore, performance was
16 symmetric for rotations about the vertical axis, whereas the words that were rotated about the
17 horizontal axis were read faster when they had positive rotation angles. In sum, previous
18 research suggests that small local changes in displayed stimuli do not alter visual processing,
19 but large orientation changes may affect the processing speed of displayed information.

Depth Change within a Curved Display

20 When viewing objects that are presented on a curved display, the distance of each
21 object to the observer's eyes depends on its location due to the depth change along the display
22 surface (Fig. 1). This variation may induce accommodative responses of the eye when the

1 observer fixates on targets that are in different display locations. The accommodative
2 responses consist of a slow component that is driven by blur in the retinal image and a fast
3 component that is driven by binocular disparity (Campbell & Westheimer, 1960; Rashbass &
4 Westheimer, 1961).

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

18 Another response to the depth change is *vergence*. It refers to the simultaneous
19 rotation of the two eyes in opposite directions in order to foveate objects while maintaining
20 fused binocular vision. The primary stimulus for vergence is the binocular disparity of the
21 scenes that are seen by the two eyes (i.e., disparity vergence), which triggers convergent (i.e.,
22 inward) or divergent (i.e., outward) corrective movements in approximately 160-180 ms
23 (Rashbass & Westheimer, 1961). Vergence can also be indirectly driven by accommodation
24 via neural crosslinks from the accommodation system (i.e., accommodative vergence), and
25 similarly, accommodation can be driven via vergence-accommodation crosslinks (e.g.,
26 Fincham & Walton, 1957; Maxwell, Tong, & Schor, 2010; 2012). Hence, depth change in

1 curved displays may initiate accommodation and vergence responses that aid object
2 perception in binocular vision. Objects that are presented at different display locations act as
3 stimuli for these responses (which take time to develop), which, in turn, affects the processing
4 speed of the displayed information.

Research on Curved Handheld Displays

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

17 Wang et al. (2007) used laminated paper prints to investigate how the curvature ($r =$
18 ± 10 cm or planar) of electronic paper, when combined with different text-background colors,
19 affects visual performance under two illuminations. By using a task in which the subjects
20 searched for a target word on a page of text, they found no difference in accuracy between the
21 curvatures. The subjects preferred to perform the task with the planar surface rather than with
22 convex or concave prints, however. Similarly, Lin et al. (2008) used laminated prints to
23 investigate the effects of curvature ($r = \pm 10$ cm or planar), illumination, and anti-reflective
24 coating on visual performance and eye strain after reading. They measured performance by

1 using the Pseudo-text search task, in which subjects search for and count the number of target
2 letters from strings of random letters that are arranged in rows, similar to normal text (Roufs
3 & Boschman, 1997). The results indicated that the presence of display coating (not the surface
4 curvature) modified search performance. Interestingly, the subjects reported less visual
5 fatigue after the pseudo-text search when curved prints were used rather than a planar surface.
6 The results of these two studies suggest that a certain amount of the surface curvature of
7 electronic paper can be tolerated without causing any notable effects on reading.

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

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

Present Study

23 This study aimed to clarify how visual performance with small curved displays depends
24 on the direction and magnitude of the display curvature. We measured performance with a

1 flexible display that was bent about its horizontal axis in order to form convex and concave
2 display surfaces with low ($r = 100$ mm) and high ($r = 50$ mm) radius curvatures. Due to the
3 expected impact of display location on the optical characteristics and visual perception,
4 performance was measured based on the function of stimuli's distance from the display's
5 center point. Visual search was selected as the experimental method. Visual search has been
6 previously utilized for various research purposes in vision science (Palmer, Verghese, &
7 Pavel, 2000; Wolfe & Horowitz, 2004) and applied vision (e.g., Greene, Brown, & Paradis,
8 2013; Ojanpää & Näsänen, 2003). Because visual displays typically contain letters and other
9 alphanumeric information, we used letters as the stimuli of the search. In Experiment 1, we
10 validated the selected method by measuring how the contrast that is needed for target
11 detection changes along the retinal eccentricity on a planar display. In Experiment 2, this
12 effect was investigated with curved displays. In Experiment 3, we investigated more detailed
13 processing of the displayed items on the concave and convex surfaces by measuring the time
14 that was required to search and identify displayed letters.

General Method

Apparatus and Environment

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

1 the effect was quite prominent (Fig. 3). In the planar state, white point variation between the
2 eccentricities was minor ($< \pm .003$) due to the small change in viewing angles ($< \pm 7^\circ$).

3 *Figure 3*

Experiment 1: Contrast-Based Target Detection with a Planar Display

4 Luminance contrast is known to affect the processing speed when searching for letters
5 (Boshman & Roufs, 1997; Ojanpää & Näsänen, 2003) and icons (Näsänen & Ojanpää, 2003),
6 as well as in target localization (Greene et al., 2013) and reading (Legge, Rubin, & Luebker,
7 1987; Ojanpää & Näsänen, 2003). Typically, performance sharply improves with increasing
8 contrast at low contrast levels and then levels off at high contrast levels (Legge et al., 1987;
9 Näsänen & Ojanpää, 2003; Roufs & Boschman, 1997). We assumed that a task that was
10 based on the detection of small contrast differences would also be a sensitive measure of
11 curvature-induced changes in visual performance. Therefore, we used a letter search task in
12 which subjects were required to detect target letters that were surrounded by other letters
13 based on the letter-background contrast.

14 The aim of Experiment 1 was to clarify two methodological aspects that were of
15 importance for the experimentation with curved displays: Whether the search task was able to
16 reveal any location-specific effects in visual processing, and whether the number of letters on
17 the screen among which the target was to be detected would affect observers' performance.
18 To consider the location-specificity of displayed objects, we measured performance based on
19 the function of distance from the display's center point (i.e., *eccentricity*) with a planar
20 display. This approach also takes into account the contrast sensitivity of the human eye,
21 which decreases from the foveal vision to the periphery (Rovamo, Virsu, & Näsänen, 1978).
22 We assumed that with brief stimulus presentations (200ms), the display eccentricity would

1 correspond to the *retinal eccentricity*, and thus, stimulus letters that appeared further away
2 from the display center would require higher target-distracter contrast for target detection.

3 To consider the effect of the number of letters on the screen, we measured observers'
4 performance with different *set sizes*. Previous research has shown that visual search that is
5 based on simple features, such as orientation or color, is independent of set size (Palmer et al.,
6 2000; Wolfe & Horowitz, 2004), but using contrast as the guiding attribute of search is a less
7 studied characteristic (Wolfe & Horowitz, 2004). When visual stimuli consist of high and low
8 contrast items, the high contrast items are typically easy to detect and hard to ignore.
9 However, when low contrast targets are presented among high contrast distractors, and the
10 experimental design allows the observer to selectively attend the low contrast targets, contrast
11 resembles other simple features that guide the search (Pashler, Dobkins, & Huang, 2004). We
12 reasoned that if the set size is irrelevant in regard to performance in the contrast-based letter
13 detection task, only one set size is needed for experimentation with curved displays.

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

Method

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

23 **Stimuli and procedure.** Stimulus characters were drawn from the set of ten Sloan
24 letters (O, S, N, Z, C, H, K, R, D, and V; Pelli, Robson, & Wilkins, 1988). The same letter

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1 was used for all of the characters of each trial. The character height (pt 20) corresponded to
2 0.42° . Letters were light grey on a mid-grey (100 cd/m^2) background. The contrast [$C_{\text{Weber}} =$
3 $(L_{\text{Letters}} - L_{\text{Background}}) / L_{\text{Background}}$] of the target letters varied from 18% to 78% ($118 - 178$
4 cd/m^2), with a step size of 12%. The contrast of the distracter letters was 90% (190 cd/m^2).
5 The stimuli were characterized on the plane through use of a spectroradiometer (PR-670
6 SpectraScan).

7 A trial began with a light grey fixation cross (0.31°) that was shown in the center of
8 the display for 500 ms (Fig. 4). After a 200 ms delay, a set of four to twelve stimulus letters
9 appeared on the circumference of an imaginary circle at one of the five eccentricities (1.6° ,
10 3.2° , 4.8° , 6.3° , or 6.8° ;) for 200 ms. The distance between two adjacent letters was always at
11 least half the eccentricity in order to avoid crowding (Bouma, 1970). Due to this requirement,
12 set size 8 was only included for $1.6^\circ - 4.8^\circ$ eccentricities and set size 12 for $1.6^\circ - 3.2^\circ$
13 eccentricities. The subjects' task was to decide whether one of the letters (target) had a
14 different (letter-background) contrast than the others (distractors) in a two-alternative forced
15 choice (2AFC) procedure. The target was present in 50% of the trials. Subjects responded by
16 pressing one of two keys on the keyboard that were marked with green ("yes") and red ("no")
17 colors. The accuracy of answers was emphasized.

18 *Figure 4*

19 Each contrast-eccentricity combination was repeated forty times in total. Eccentricity
20 and target contrast varied from trial to trial in a random order. A stimulus block consisted of
21 half the trials that were needed for a set size and each block contained trials for one set size
22 only. Presentation order for the blocks was counterbalanced between the subjects. Subjects
23 were allowed to take short breaks between the blocks. Before the actual experiment, the
24 subjects were trained on the task for ten minutes. During this period, the incorrect answers

1 were signaled with a sound mark, which was not used in the actual experiment. The
 2 experiment was divided into several sessions, with each starting with a short training period.

3 **Analysis of results.** Search performance was measured as the *sensitivity* of target
 4 detection with the *d-prime* (d') measure of Signal Detection Theory. D-prime is based on the
 5 proportions of the four response types (hit, miss, correct refusal, false alarm), and it is
 6 independent of response criteria (see Stanislaw & Todorov, 1999). The values of d' were
 7 calculated by using the formula $d' = z(H) - z(F)$, where H = hit rate, F = false alarm rate, and
 8 $z()$ is a probit function. Trials with a response time over 10 seconds (< 0.2 %) were excluded
 9 from the data. The mean response time was 740 ms ($SD = 381$ ms).

10 Statistical significance of d-prime values was tested by using a random intercept model
 11 (Linear Mixed Models, LMM) that treated *Eccentricity* (1.6°, 3.2°, 4.8°, 6.3°, 6.8°) and *Set*
 12 *size* (2, 4, 8, 12) as fixed factors and *Subject* as a random intercept. Post hoc comparisons
 13 were carried out by using the Bonferroni correction. The effect size of the full multilevel
 14 model was estimated with the reduction in mean square prediction error according to
 15 Snijders' and Bosker's (1999) formula:

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

$$= 1 - \frac{\hat{\sigma}^2(\text{full}) + \tau_0^2(\text{full})}{\hat{\sigma}^2(\text{null}) + \hat{\tau}_0^2(\text{null})},$$

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

Results and Discussion

21 The sensitivity of target detection (d') with the planar display is illustrated in Figure 5.
 22 Sensitivity depended on *Eccentricity* [LMM $F(4,28) = 46.46, p < .0001$] because the d-prime

1 decreased when the distance from the center increased from 1.6° ($d' = 2.66$) to 3.2° ($d' =$
2 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° ($d' =$
3 1.07 , $p = .007$). *Set size* did not affect the performance [$F(3,28) = 1.84$, $p = .164$]. *No*
4 *Eccentricity x Set size* interaction was obtained [$F(7,28) = 1.33$, $p = .276$]. The observed effect
5 size of the full model was $R^2 = .77$.

6 *Figure 5*

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

Experiment 2: Contrast-Based Target Detection with Curved Displays

13 The aim of Experiment 2 was to investigate whether the detection of displayed items
14 depends on the direction and magnitude of the display curvature. We reasoned that by
15 comparing target detection between the display variants at a given eccentricity, we could
16 demonstrate the effects of the direction and magnitude of curvature on the sensitivity and
17 accuracy of the search. We hypothesized that performance would decrease with increasing
18 curvature magnitude and that performance with convex displays would be inferior to
19 performance with concave displays.

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

1 the subjective evaluations before they are seen in the objective performance measures
2 (Boschman & Roufs, 1997; Pölönen et al., 2008; Wang et al., 2007).

3 *Figure 7*

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

12 Hence, the results indicated that performance in the contrast-based detection task was
13 defined by the targets' location relative to the display center rather than by the curvature of
14 the display. The targets were detected similarly across the curvatures despite their large
15 variation in letter slants (up to 53° ; Table 1) and the foreshortening of retinal image (up to
16 49% of target height). Previous research has shown that perspective distortions are effectively
17 corrected by the visual system. For instance, processing times for rotated words have been
18 shown to remain at a constant level for up to $\pm 60^\circ$ vertical and horizontal rotation (Grossman
19 et al., 2007; Larson et al., 2000). Consistent with these findings, our results demonstrated that
20 displayed targets were detected similarly independent of the local curvature, which indicates
21 that efficient compensation of retinal distortions was produced by the curved display surface.
22 This suggests that under optimal viewing conditions, simple target detection from a small
23 (4.5") curved display can maintain the level that is reached with the planar display, even when
24 the display is bent to ± 50 mm radius curvature.

1 A plausible reason for the small effect of curvature on performance is provided by the
2 high native CR of the display. Despite the large variation in viewing angles between the
3 curvature variants and in brightness reduction towards the display edges (Table 1), the
4 15 000:1 CR was able to reproduce the greyscale at a sufficiently steady level across the
5 curvatures. Because the perceived contrast for a particular display location did not differ
6 between the curvature variants, performance in the contrast-based target detection was
7 defined by the retinal eccentricity alone. Consequently, performance with the curved displays
8 closely resembled the performance that was obtained with the planar display. Because the task
9 was based on the perception of the luminance contrast, variation in the display's white point
10 did not even alter performance (Table 1; Figure 3).

11 However, the contrast-based detection task that was employed in Experiment 2 did not
12 require detailed processing of displayed information. Instead, it appears that with a large
13 enough contrast difference, the target stood out among the otherwise identical distractors,
14 which is similar to findings that are typically reported after using a single feature search
15 (Palmer et al., 2000; Pashler et al., 2004; Wolfe & Horowitz, 2004). Although curving the
16 display did not affect simple target detection, it might still affect performance in visual tasks
17 that require a more elaborate analysis of the displayed information (Wolfe & Horowitz,
18 2004). Furthermore, because the lowered contrast sensitivity of the eye generally made visual
19 processing difficult at high eccentricities, it is possible that certain between-curvature effects
20 were covered. Performance differences outside the central display are of special importance in
21 regard to curved displays because the local changes are largest when they are close to the
22 display edges. These effects were further investigated in Experiment 3.

Experiment 3: Threshold Letter Search Time with Curved Displays

23 The aims of Experiment 3 were twofold: First, we were interested in whether curving
24 the display would affect performance in a task that required detailed visual analysis of the

1 displayed items. Second, we wished to clarify the curvature effect for areas outside the central
2 display. For these purposes, we employed another visual search task in which subjects
3 searched for a target letter that was surrounded by other letters based on *letter identity* and
4 measured the time that was required for a successful search (i.e., *threshold search time*).
5 Because letter identity is not a preattentive feature that would facilitate target detection
6 (Wolfe & Horowitz, 2004), the subject must serially fixate on and identify each letter on the
7 screen in order to find the target. The time that is required for this process greatly depends on
8 the difficulty of the task (e.g., number of distracters) and on the viewing conditions (e.g.,
9 display curvature), which modify the fixation durations and the number of fixations that are
10 needed for the search (Rayner, 2009). Furthermore, target processing in peripheral vision as
11 opposed to central vision requires more eye movements and more time (Scialfa & Joffe,
12 1998).

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

Method

20 **Subjects.** Subjects were eight students and staff of Aalto University (age range: 23-33
21 years, mean: 27.4 years). One of them was an author of this study (TM), and the others were
22 naïve to the purpose of the experiment. All of the subjects reported normal or corrected-to-
23 normal vision and wore their typical eye-correction equipment during the experiment. They
24 were screened for normal visual acuity and contrast sensitivity, similar to Experiments 1 and

1 The duration of the stimulus presentation was varied through the use of an adaptive
2 staircase algorithm (Wetherill & Levitt, 1965; cf. Näsänen & Ojanpää, 2003; Ojanpää &
3 Näsänen, 2003). In the beginning of each block, the presentation duration was 1000 ms. After
4 an incorrect response, the duration of the next stimulus presentation was increased by a factor
5 1.26. Conversely, after three consecutive correct responses, the duration of the next stimulus
6 presentation was decreased by the same factor. This staircase procedure was continued until
7 the eighth reversal on the staircase. A threshold estimate that indicated a 79% probability of
8 the subject choosing a correct answer was defined as the average of these reversals. The first
9 5 trials were not taken into account in this threshold estimate.

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

14 **Analysis of results.** Threshold search times were defined for five display curvatures,
15 at four eccentricities, and with two set sizes. The average number of trials that was needed for
16 a threshold estimate was 44 ($SD = 12$) and 41 ($SD = 11$) for set sizes 8 and 12, respectively.
17 Statistical significance of the estimates was tested through use of the LMM by treating
18 *Curvature* (high concave, low concave, plane, low convex, high convex), *Eccentricity* (1.6°,
19 5.3°, 5.9°, 6.6°), and *Set size* (8, 12) as fixed factors and *Subject* as a random intercept. Post
20 hoc comparisons were carried out by using the Bonferroni correction.

Results and Discussion

21 Threshold search times are plotted in Figure 9. Consistent with our hypotheses, the
22 LMM indicated significant main effects of *Curvature* [$F(4,238) = 7.61, p < .0001$],
23 *Eccentricity* [$F(3,238) = 60.33, p < .0001$], and *Set size* [$F(1,238) = 41.16, p < .0001$]. The
24 observed effect size of the full model was $R^2 = .34$. Thresholds were higher for the high

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1 curvatures ($r = \pm 50$ mm) than the low curvatures ($r = \pm 100$ mm; $p < .01$), whereas
2 performance with the low curvatures and the planar display did not differ ($p > .05$). The
3 prolonged search times were consistent with the subjects' comments regarding the difficulty
4 of the task. Thresholds were also higher for targets that were presented at intermediate
5 eccentricities (5.3 - 5.9°) than for targets that were near the display center (1.6° ; $p < .001$), and
6 the highest thresholds were obtained near the display edges (6.6° ; $p = .002$). As expected, set
7 size 12 resulted in longer threshold search times than set size 8.

8 *Figure 9*

9 A significant *Curvature x Eccentricity* interaction was also found [$F(12,238) = 2.21$, p
10 $= .012$; Fig. 10]. Close to the display center (1.6°), threshold durations for convex displays
11 were slightly shorter than thresholds for planar and concave displays. As the distance from the
12 display center increased, performance with all of the curved displays decreased in relation to
13 performance with the planar display, however. With convex displays, this performance drop
14 peaked at approximately 6° , which indicated that the convex displays had 100 ms (for low
15 convex) to 230 ms (for high convex) higher thresholds than the planar display at that distance.
16 With concave displays, the relative change was smoother, with there being a 70 ms (for low
17 concave) to 130 ms (for high concave) relative increase at peak thresholds of approximately
18 5° . These findings indicate that performance with convex displays and with a high convex
19 curvature, in particular, was more dependent on the display location than performance with
20 the concave counterparts was. In fact, average thresholds with the high convex curvature
21 varied from 320 ms to 730 ms (> 400 ms), depending on eccentricity, whereas the variance
22 with the low convex curvature (300 ms) and both concave curvatures (250 ms) was smaller.

23

24 *Figure 10*

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

8 Whereas Experiment 2 indicated no difference in target detection between the
9 curvature variants, Experiment 3 demonstrated that search speed for the displayed targets was
10 clearly reduced with high curvature magnitudes. This reflects the different requirements of the
11 visual tasks that were employed in the experiments. Interestingly, the constant performance
12 across the curvatures in the contrast-based target detection (Experiment 2) suggests that
13 prolonged threshold letter search times that were associated with the high curvature
14 magnitudes (Experiment 3) were not due to changes in contrast. The reduced performance
15 must, therefore, result from other optical characteristics and local changes in stimulus features
16 (Table 2).

17 Both brightness and the white point underwent a notable change when the display was
18 bent to high radius curvatures. Although the perceived contrast of the display was not
19 affected, these changes likely interacted with other local changes in the displayed stimuli. The
20 letters on the high curvatures were slanted over 50° at their highest slant. Although this high
21 amount of perspective change can be corrected by the vision system without there being a
22 notable effect on the observer's performance (Grossman et al., 2007; Larson et al., 2000;
23 Rosinski et al., 1980; Vishwanath et al., 2005), the resulting foreshortening in stimulus size
24 may have slowed down the speed of search in the present case. The size reduction from the
25 central display (1.6°) to near the display edges (6.6°) was approximately 28% with high
26 concave curvatures and 46% with high convex curvatures. The corresponding values for the

1 low concave and convex curvatures (both with up to 25° letter slants) were 4% and 16%,
2 respectively (Table 2). The larger variation in character height would also explain why
3 performance with convex curvatures depended more on eccentricity than performance with
4 the concave curvatures did.

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

General Discussion

13 The effect of display curvature on visual performance depended on the type of visual
14 task. In the contrast-based target detection task (Experiments 1 and 2), the direction and
15 magnitude of curvature did not affect performance (when compared to the planar display). In
16 the search task that required more elaborate processing of displayed items in order to identify
17 the targets (Experiment 3), performance was clearly reduced with high radius curvatures ($r =$
18 ± 50 mm), especially in regard to the convex form. In both tasks, performance strongly
19 depended on the distance from the display center at which the displayed items appeared. In
20 particular, performance beyond 6° eccentricity severely declined.

Target Detection and Speed of Search with Curved Displays

21 In Experiment 2, the displayed targets were detected similarly across the curvatures.
22 The sensitivity and accuracy of contrast-based target detection were determined by the

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

20 However, the prolonged processing times that were associated with the high curvature
21 magnitudes ($r = \pm 50$ mm) in Experiment 3 indicated that processing visual details becomes
22 more laborious with curved displays. The processing times were further increased by adding
23 to the number of to-be-processed items that was on the display. Because the perceived
24 contrast of the stimuli did not differ between the curvatures (Experiment 2), the increased
25 demands most likely did not result from poor legibility of the letters. Instead, the prolonged
26 threshold durations could reflect the amount of local changes in visual stimuli with which

1 observers must cope while performing the task. For instance, at 6.6° eccentricity, the high
2 curvature magnitudes resulted in an average change of 53° for the viewing angle and in an
3 average 37% reduction in letter height. The corresponding values with low curvature
4 magnitudes ($r = \pm 100$ mm) were 23° for the viewing angle and 9% for the letter height.

5 Because the thresholds for the low radius curvatures did not differ from the planar
6 display, it appears that a notable amount of changes were tolerated by the visual system
7 before the processing speed of the displayed items was slowed down. This finding is
8 consistent with previous research related to visual performance with curved surfaces. Wang et
9 al. (2007) and Lin et al. (2008) found that ± 100 mm radius curvature had no influence on
10 visual performance with simulated electronic paper. Similarly, results by Grossman et al.
11 (2007) and Larson et al. (2000) demonstrated that rotations of displayed text have negligible
12 effects up to a ± 55 - 60° change (after this, performance declines sharply). When combined
13 with the present results, these findings suggest that low curvature ratios do not alter visual
14 performance with small displays in optimal viewing conditions. However, curvature
15 magnitudes at a radius size of approximately 50 mm already cause a noticeable decrease in
16 the speed of visual processing. Such decrements are particularly evident with convex display
17 surfaces.

Limitations and Future Directions

18 Certain aspects must be considered in regard to the generalization of the present results.
19 First, because the study aimed to investigate baseline visual performance with curved displays
20 without there being intervening environmental factors, the experiments were conducted in
21 dim indoor lighting. The applicability of the results for other lighting conditions is, therefore,
22 limited. This is particularly true in regard to bright outdoor lighting because the current
23 flexible technologies still encounter problems regarding sunlight readability. With emissive
24 OLED displays, performance is limited due to the metal electrodes in the display structure.

1 These electrodes have high reflectance, which reduces the display contrast under strong
2 external light (Singh et al., 2012; Yang et al., 2005). Reflective technologies that are used in
3 electronic paper utilize ambient light as the light source rather than a display backlight, and
4 performance with such displays should, therefore, improve with an increasing intensity of
5 light. There are always surface reflections on electronic paper, however, and excess
6 illumination can cause additional side effects, such as glares, that further impair the ambient
7 contrast (e.g., He, Torrance, Sillion, & Greenberg, 1991; Lin et al., 2008).

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

20 Second, future research should clarify how visual processing with curved displays is
21 influenced by the displayed contents. The visual stimuli in the present study consisted of
22 single legible letters that were presented at a noticeable distance from each other. Still,
23 increasing the set size of the displayed items from 8 to 12 significantly decreased the
24 observers' performance on the identification task. This suggests that with high-density
25 information, the degradation would be more severe. Furthermore, the spatial frequency
26 content of the displayed information affects the accommodation response of the eye (Okada et

1 al., 2006). With high-frequency content, changes in retinal blur are easily detected, which
2 triggers corrective actions by the vergence-accommodation system. With low-frequency
3 content, the blur is more difficult to detect, and corrective actions do not occur. Because the
4 accommodative corrections take time to develop (Campbell & Westheimer, 1960; Fincham &
5 Walton, 1957), the frequency content can greatly modify the processing speed of information
6 with curved displays in which the depth change between display locations generates retinal
7 blur. In addition to resulting from the high density of displayed information, the effect can
8 result from the high spatial resolution of the display.

Conclusions and Implications

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

19 As device concepts approach real products and technology matures, understanding the
20 advantages and limitations of such concepts from the perspective of human perception and
21 performance becomes increasingly important. The present study provides a baseline for visual
22 performance with deformable displays by demonstrating how the direction and magnitude of
23 static curvature affect visual search with small displays under optimal viewing conditions. By
24 showing that observers' performance was independent of curvature in simple detection tasks

1 and with low radius curvatures ($r = \pm 100$ mm), we demonstrate that the visual system
2 compensates for a large degree of the changes that are caused by curving in high-quality
3 displays. With high curvature magnitudes ($r = \pm 50$ mm), the identification of displayed items
4 clearly decreased in speed, however. This was particularly true of the convex curvature, with
5 which the speed of processing strongly depended on the display location. Because the
6 curvature effects are supposed to be intensified by high intensity light, using such high
7 magnitude curvatures in portable devices should be avoided. Furthermore, critical information
8 should not be presented near the display edges because both sensitivity and the speed of
9 search were reduced in locations that were beyond $5-6^\circ$ from the display center. Finally, the
10 future design of display applications should consider that visual performance with curved
11 displays depends on the characteristics of the display and environment, as well as the current
12 visual task. Visual performance and ergonomics with curved display surfaces should remain
13 an active focus of research as long as visual processing is the primary information channel in
14 display applications.

15 Key points

- 16 • Viewing a curved display differs from viewing a planar display due to changes in
17 display optics and geometry, viewing angle, and accommodative responses of the eye.
18 These changes can affect visual perception and performance.
- 19 • Here we compared visual performance with a flexible display in a planar and four
20 curved configurations. The curved displays differed with respect to the direction (i.e.,
21 concave, convex) and magnitude (i.e., low, high) of curvature.
- 22 • The direction or magnitude of curvature did not change users' sensitivity for target
23 detection in a simple target detection task. However, the speed of target identification

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VISUAL PERFORMANCE WITH CURVED DISPLAYS

1 Table 1

2 *Local curvature effects in Experiment 2*

Measure ^a	Planar	Concave		Convex	
		<i>High</i>	<i>Low</i>	<i>Low</i>	<i>High</i>
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 (°) <i>M ± SEM</i>					
1.6°		9.44 ± 1.43	.72 ± .71	4.72 ± .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 (°) <i>M ± SEM</i>					
1.6°	25.36	25.07 ± .07	25.32 ± .01	25.18 ± .04	24.79 ± .13
3.2°	25.33	24.24 ± .24	25.19 ± .04	24.67 ± .15	23.25 ± .45
4.8°	25.24	21.66 ± 1.37	24.79 ± .06	23.11 ± .22	18.75 ± .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°	-0.002; .000	.000; .004	-0.001; .001	.000; .000	-0.003; .000

VISUAL PERFORMANCE WITH CURVED DISPLAYS

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

- 1 *Note.* High = ± 50 mm radius curvature; Low = ± 100 mm radius curvature. ^aAt standard
- 2 eccentricities (1.6°- 6.8°) defined with the planar display. ^bDefined at display's vertical
- 3 midline, where the largest changes occur. ^cOutside the measurement range [-50°, 50°].

VISUAL PERFORMANCE WITH CURVED DISPLAYS

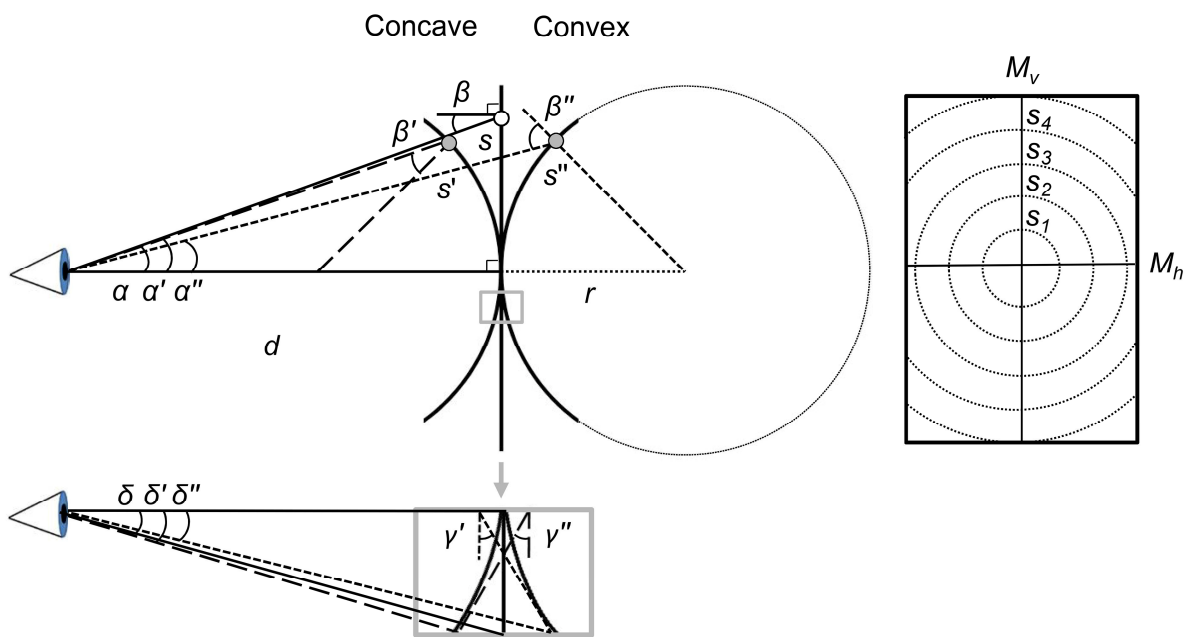
1 Table 2

2 *Local curvature effects in Experiment 3*

Measure ^a	Planar	Concave		Convex	
		<i>High</i>	<i>Low</i>	<i>Low</i>	<i>High</i>
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 (°) <i>M ± SEM</i>					
1.6°		9.43 ± 1.33	4.72 ± .66	4.72 ± .66	9.43 ± 1.33
5.3°		43.75 ± .83	21.88 ± .42	21.88 ± .42	43.75 ± .83
5.9°		45.20 ± .58	22.60 ± .29	22.60 ± .29	45.20 ± .58
6.6°		51.80 ± .67	25.90 ± .33	25.90 ± .33	51.80 ± .67
Target height (') <i>M ± SEM</i>					
1.6°		16.72 ± .04	16.88 ± .01	16.79 ± .03	16.53 ± .08
5.3°		13.45 ± .13	16.37 ± .02	14.83 ± .07	10.92 ± .02
5.9°		13.23 ± .09	16.34 ± .01	14.71 ± .05	10.58 ± .14
6.6°		12.08 ± .12	16.15 ± .02	14.07 ± .07	8.90 ± .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 (Δu'; 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

VISUAL PERFORMANCE WITH CURVED DISPLAYS

- 1 *Note.* High = ± 50 mm radius curvature; Low = ± 100 mm radius curvature. ^aAt standard
- 2 eccentricities (1.6° - 6.6°) defined with the planar display. ^bDefined at display's vertical
- 3 midline, where the largest changes occur. ^cOutside the measurement range [-50° , 50°].



1 *Figure 1*

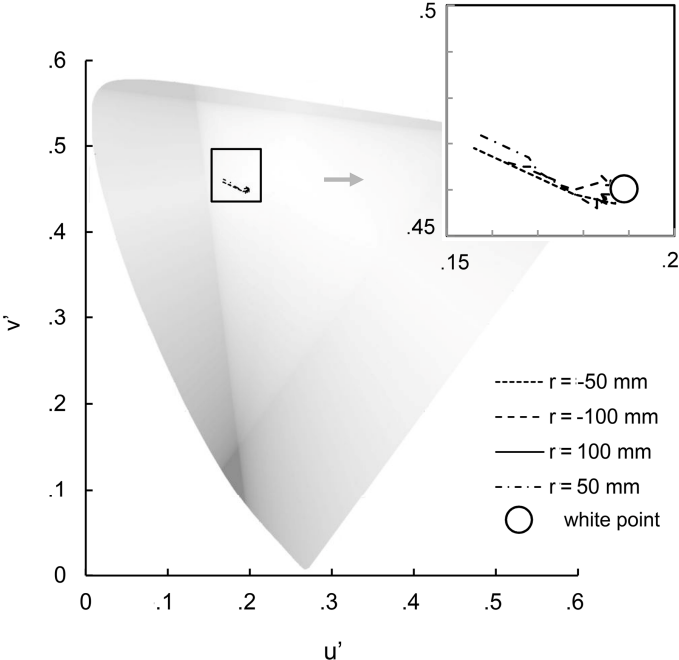
2 Display geometry with curved displays. Differences between concave and convex
 3 that are curved about the horizontal axis and a planar surface from a constant viewing
 4 distance (d). The depth change is in the opposite direction in regard to concave (-) and convex
 5 (+) displays. Radius curvature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

VISUAL PERFORMANCE WITH CURVED DISPLAYS



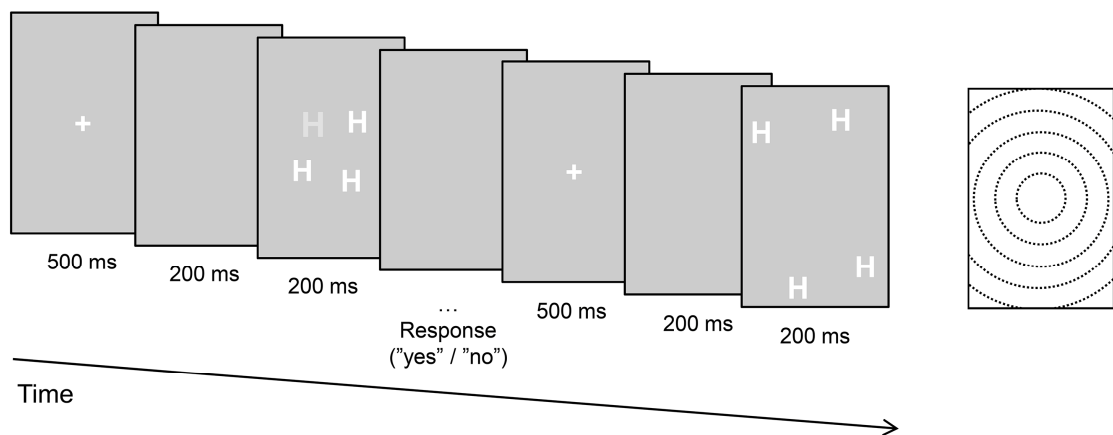
1 *Figure 2*

2 Experimental setup and display curvatures. Curvatures from left to right are *high concave* ($r =$
3 -50 mm), *low concave* ($r = -100$ mm), *planar*, *low convex* ($r = 100$ mm), and *high convex* ($r =$
4 50 mm).



1 *Figure 3*
2 White point variation in curved displays (CIE 1976 coordinate). Increasing curvature
3 magnitude and eccentricity enlarges the viewing angle, which, in turn, shifts the white point
4 towards the green primary.

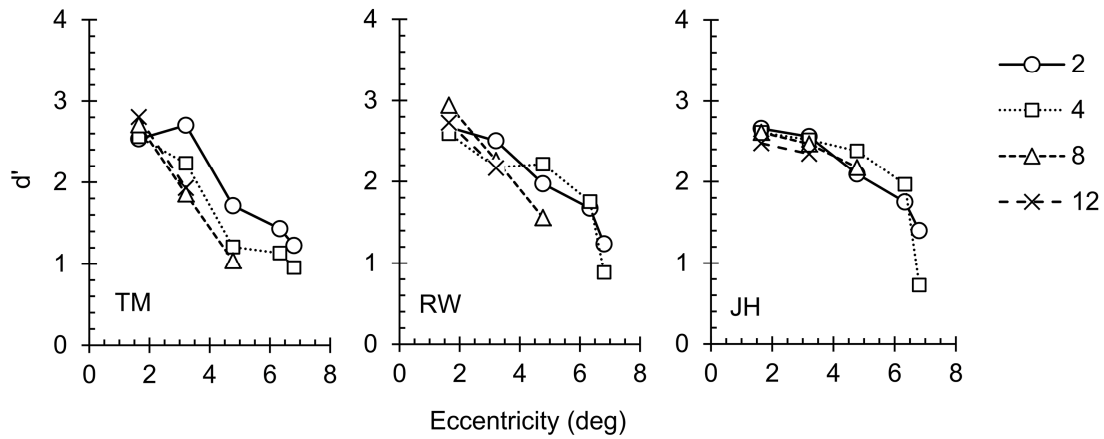
VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 4*

- 2 Contrast-based target detection task (Experiments 1 and 2). Grey sequence (left) illustrates
3 display events during two consecutive trials. The subjects' task was to decide whether a target
4 (i.e., letter with lower contrast) appeared among the distracters (i.e., otherwise identical
5 letters) or not. White display (right) illustrates the eccentricities (1.6° , 3.2° , 4.8° , 6.3° , and
6 6.8°) at which letters were presented.

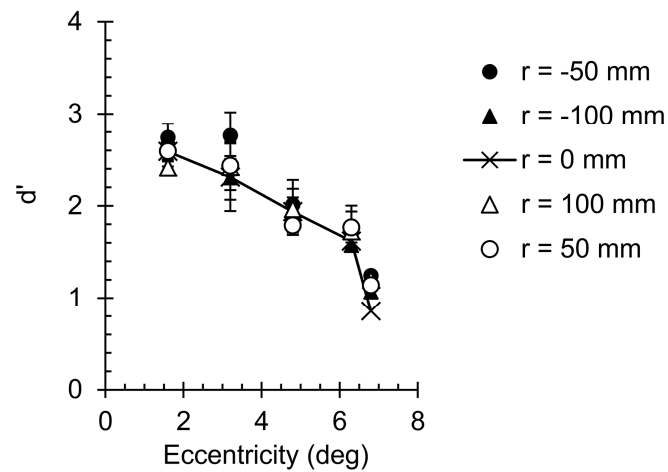
VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 5*

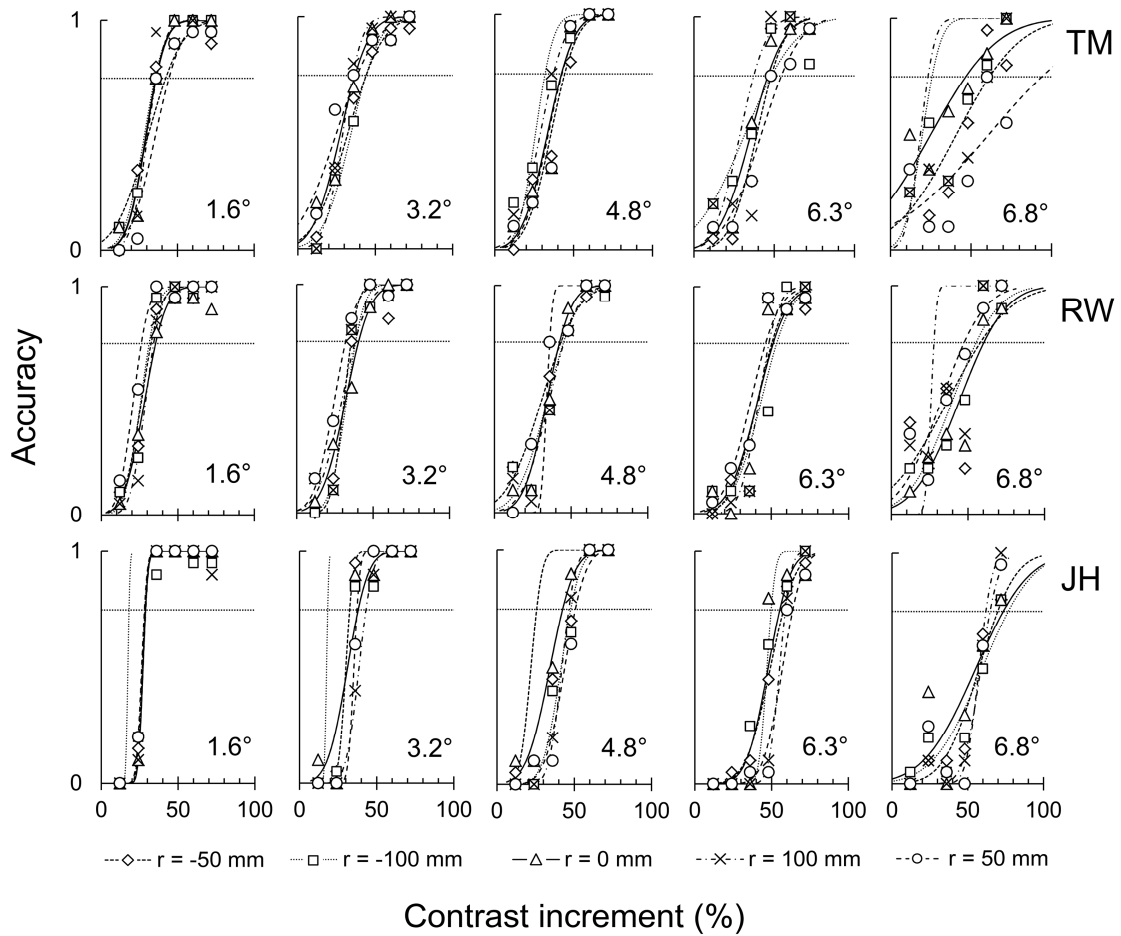
2 Sensitivity of target detection (d') with the planar display (Experiment 1). The figure plots
3 sensitivities as a function of eccentricity (measured at 1.6°, 3.2°, 4.8°, 6.3°, and 6.8°) with
4 four set sizes (2, 4, 8, and 12). The results for the three subjects (TM, RW, and JH) are
5 depicted in different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

VISUAL PERFORMANCE WITH CURVED DISPLAYS



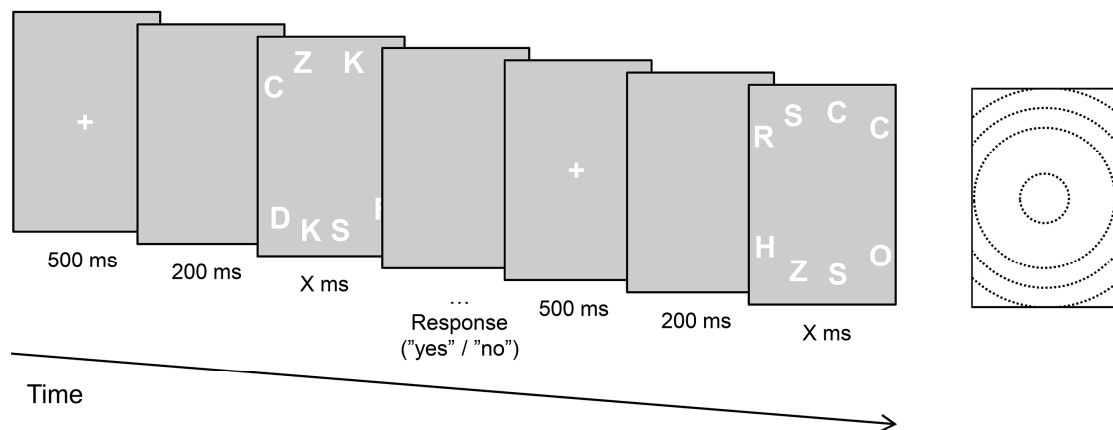
- 1 *Figure 6*
- 2 Sensitivity in contrast-based target detection (d') with curved displays (Experiment 2). Mean
- 3 ($n = 3$) results are plotted as the function of eccentricity from the display center. A solid line
- 4 indicates performance with the planar display. Filled markers are concave curvatures, and
- 5 open markers are convex curvatures. Error bars represent the standard errors of the mean.

VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 7*
 2 Accuracy of target detection with curved displays (Experiment 2). The results are plotted as
 3 the function of the target-distractor contrast for three subjects (TM, RW, JH) at five
 4 eccentricities (1.6-6.8°), separately. Each data point is based on twenty repetitions. The
 5 horizontal line indicates a 0.75 threshold.

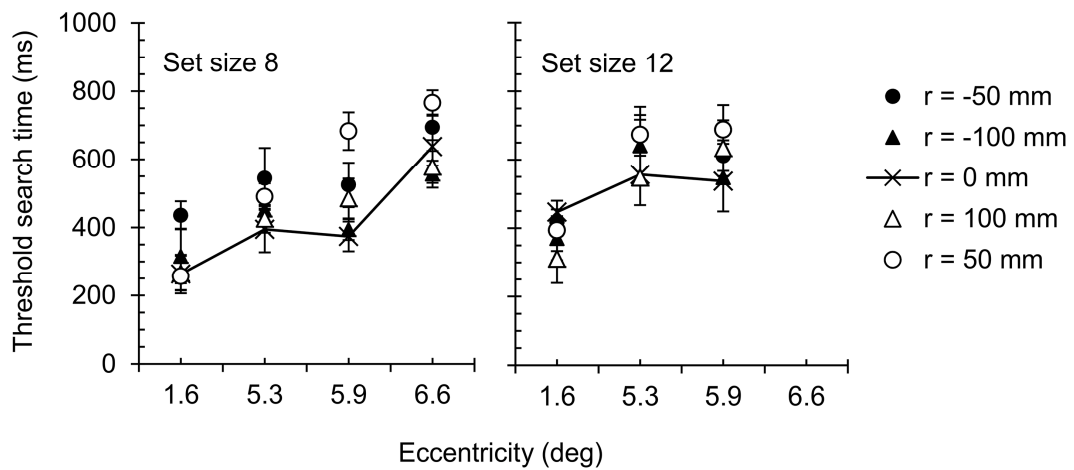
VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 8*

2 Letter search task (Experiment 3). The grey sequence (left) illustrates display events during
3 two consecutive trials. The subjects' task was to decide whether a target letter (H) appeared
4 among the distracter letters. The presentation duration for the stimuli varied depending on the
5 subject's performance. The white display (right) illustrates the eccentricities (1.6°, 5.3°, 5.9°,
6 and 6.6°) at which the letters were presented.

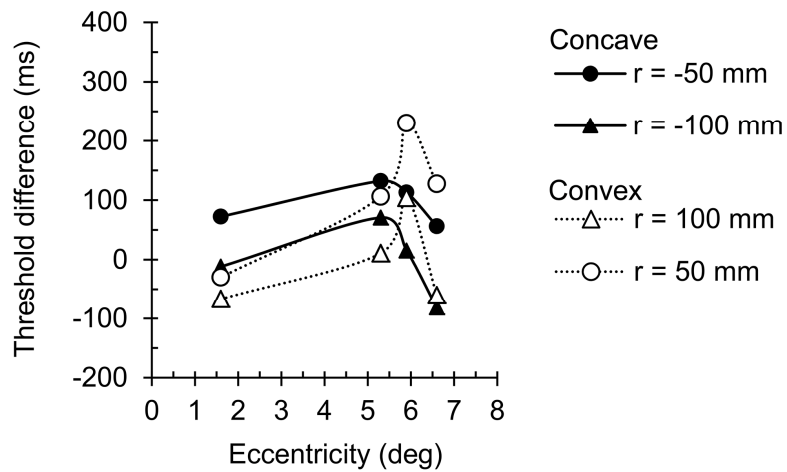
VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 9*

2 Threshold search times with curved displays (Experiment 3). Mean ($n = 8$) results are plotted
3 as the function of eccentricity for two set sizes, separately. Solid lines indicate the thresholds
4 for the planar display. Filled markers indicate concave displays, and open markers indicate
5 convex displays. Error bars represent the standard errors of the mean.

VISUAL PERFORMANCE WITH CURVED DISPLAYS



1 *Figure 10*

2 Effect of display curvature on threshold search times (Experiment 3). Performance with
3 concave and convex displays relative to the planar display ($D_{\text{Curved}} - D_{\text{Plane}}$) is illustrated as
4 the function of eccentricity. The figure combines the data for the set sizes 8 and 12 illustrated
5 in Figure 9. Performance at the 0 level corresponds to performance for the planar display.
6 High positive values demonstrate large decrements. The results are calculated over the two set
7 sizes. Filled markers indicate concave curvatures, and open markers indicate convex
8 curvatures. Note that performance with low convex and low concave curvatures did not differ
9 from the performance for the planar display.