Do consumers prefer curved monitors? Assessment of preferred curvature and readability performance

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ABSTRACT
Computer users have a wide variety of computer display preferences, but a contentious argument has been used in favor of the curved display. In this context, this study investigated the users' curvature preference for six different content types, and compared the usability of the curved and flat panels in terms of readability performance. A 27-inch bendable display panel was devised for the experiment to enable users to adjust the curvature manually. In the first experiment, the study participants searched for the optimal radii of curvature when the six content types were mounted in sequence on the bendable display, which confirmed the users' preference for the curved display over the flat display. The following experiment demonstrated that the study participants showed improved readability on the curved display, which supported the study hypothesis. The results of the experiments in this study suggest that the curved display will help improve the work efficiency of consumers.

1. Introduction
Since curved televisions were introduced in the market, the consumers have paid attention to this new viewing experience, which has resulted in a noticeable increase in sales [1,2]. Experts forecasted further market growth and predicted the expansion to other display products. More recently, leading display manufacturers launched curved monitors, and a sharp increase in sales has also been observed [3,4].

Despite the market growth, however, there have been few studies that provide empirical evidence of the advantage that the consumers can derive by using a curved display [5]. In general, it has been said that people prefer curvilinear to rectilinear objects [6]. From a simple geometric form to a complex form, curvilinear objects are likely to be preferred to rectilinear objects. Based on such conception, it has been anticipated that the curved display will be preferred to the flat display [7]. Indeed, the manufacturers advertise the excellence of the curved displays based on the principle of human vision; for instance, it is often quoted that the human vision system has evolved to perceive three-dimensional surroundings rather than a flat surface [8,9]. According to this assertion, the viewing distance can be better maintained when one watches a curved display, which may contribute to more comfortable and immersive viewing. In addition, Kelley’s study demonstrated that the curved display can more effectively avoid the reflection of the ambient light source by testing the reflection performance of two of the most recently released models of the curved television [10].

With the rising interest in the curved display, there have been a number of researches on the optimal curvature of such display, especially in relation to the curved TV [11,12]. For instance, Park et al. proposed a model that can calculate the proper curvature, which maximizes the preference and minimizes the distortion. Still, the aforementioned researches have a limitation in that the experiments were performed with fixed radii rather than letting the users find their own optimal curvature.

Thanks to such previous studies, the superiority of the curved display was explained in terms of the human vision system, but its task efficiency was focused on less. Task efficiency is crucial in the field of curved monitor research because the users’ behavior mostly consists of creating or reading documents [13]. Along with the market interest in the curved display, some recent studies provided empirical evidences that such display has a strong potential to appeal to the consumers in terms of usability and aesthetic appearance. For example, Suk et al.
found that the optimal radius of curvature of a display varies depending on the display size, and may increase as the display becomes larger [14,15]. Moreover, Ahn et al. compared a flat display TV with a curved display TV with respect to the locations of the focused points, posture, and satisfaction, and found that the study participants preferred tilted angles [16]. With regard to the work environment, some experts have also tried to determine the optimal ergonomic condition of a curved display based on the users’ subjective judgments [17]. Häkkinen et al. evaluated the users’ reading experience on curved-paper-like displays and revealed that a concave surface improves the reading performance [18]. Similarly, Shupp et al. tested the task efficiency of multiple monitor interfaces and found that the curved arrangement of multiple displays enhanced the task performance compared to flat interfaces [19].

Likewise, although previous studies tried to evaluate the task performance of the curved display in contrast to that of the flat display, and revealed its optimal ergonomic condition, there has been little consideration of the usability of the curved display in the monitor-sized display. Nevertheless, to ensure that the curved display can be used effectively and efficiently, developers should be aware of the physical and cognitive capabilities and limitations of the people who will use the product. In this given context, there is clearly a need to investigate whether consumers prefer the curved display, and if they do, what reasons underlie such preference.

In this regard, in this paper, the reading performances of the users on a monitor-sized curved display and a flat display were examined, and the two display types were compared in terms of usability. Reading performance or readability includes the following in its dictionary definition: (a) legibility; (b) reading ease; and (c) interest value of a text. As people deal with a huge amount of texts with computers [20], the reading ease or legibility of the text is important. The present study has two key contributions. First, the study participants’ subjective preference for a curved monitor was investigated, and its optimal radii were analyzed. Second, it empirically investigated the advantages of the curved display by evaluating its usability.

2. Experiment plan

This study involved two experiments. In Experiment 1, the influence of each content type on the optimal radii of curvature was assessed by mounting six content types on a bendable display panel. Next, Experiment 2 was conducted to compare the readability of the flat and curved panels, and the usability of the curved display was determined based on the experiment results. The preparation of the experiment stimuli is explained in the following section.

2.1. Experimental material

A bendable display panel was devised so that the users could flexibly vary its curvature. As illustrated in Figure 1, the radius can be easily modified by pulling or pushing the bar handle. When the handle is pulled, the radius

Figure 1. Illustration of bendable display panel (above)/pulling and pushing procedure at bendable display panel to make an optimal radius of curvature to read (below).
decreases up to 200 mm, and when it is pushed, the radius increases. When this tension between push and pull reaches an equilibrium state, the panel becomes flat. If the bar handle is pushed farther, the panel takes on a convex shape that may reach 1000 mm. The size of the display panel is 27 inches diagonally, with a 16:9 aspect ratio, and the display panel is labeled ‘27-inch panel’ throughout this paper.

To simulate the monitor contents displayed on the 27-inch panel, six types of contents were prepared. It is generally known that computer users spend most of their computer time surfing the Web, creating documents or presentations, reading books, watching movies, or playing games [20]. Therefore, as presented in Figure 2, the contents used in this study consisted of (a) a photograph (human faces); (b) a worksheet (Microsoft Excel); (c) a computer graphic image (Microsoft Windows default background); (d) a geometric image; (e) a 3D game scene; and (f) plain text. With regard to the plain text, five variations were made, each containing 2500 Korean letters. The texts were presented with a San Serif typeface and a 12-point font size, which was cited in a previous study as adequate for comfortable reading [21].

3. Experiment 1

Experiment 1 was performed to determine the optimal radius of the 27-inch panel, and to investigate how it changes while the user views various types of visual contents.

3.1. Method

A total of 30 college students (15 males and 15 females) participated in Experiment 1. The average age of the participants was 21.93 years, with a standard deviation of 2.91 years. All the participants were paid volunteers.

The participants were seated at a 60 cm distance from the display panel, and explored the optimal radius of curvature for viewing the five content types ((a–e) in Figure 1). They also had an option to choose the flat shape as the optimal form. In Experiment 1, the plain text ((f) in Figure 1), whose optimal radius of curvature was planned to be investigated in Experiment 2, was excluded. The experiment room was lit with 6500 K, and the illuminance was 600 lx. Under this illumination, the luminance reflected from the white area in each content image was measured as 77.40 cd/m². The experimenter attached to the panel one of the five visual contents, which had been printed on glossy paper, and the study participants pulled or pushed the bar handle until they found what they believed to be the optimal radius of curvature for each content. The five contents were presented in random order, and the optimal radii found by the participants were recorded.

3.2. Results of Experiment 1, and analyses thereof: optimal radii of curvature

The mean of the optimal radii of curvature of the six content types was calculated to determine if the curved display could appeal to the study participants consuming different content types. The radius with a convex
Table 1. Comparison of the mean (M) and standard deviation (SD) of the optimal radius of curvature for six types of monitor contents ((a–f) correspond to Figure 1).

| Monitor contents | Mean radii (mm) | SD (mm) |
|------------------|----------------|---------|
| (a) Human faces  | 661.00         | 279.12  |
| (b) Worksheet    | 900.00         | 811.66  |
| (c) Computer graphic | 827.67    | 394.57  |
| (d) Geometric image | 776.67    | 537.51  |
| (e) 3D game      | 625.67         | 243.82  |
| (f) Plain text   | 666.67         | 275.22  |

shape was not selected in any of the given contents. Even when the study participants were given an opportunity to choose the flat shape as the optimal panel form, all of them chose the curved shape as such.

As shown in Table 1, the study participants found the worksheet as having the largest radius for viewing (900.00 mm), followed by the computer graphic image (827.67 mm) and the geometric image (776.67 mm). This study also demonstrated that the study participants preferred the smallest mean radii of curvature for the 3D game among the chosen contents, which confirms the results of the study recently conducted by Choi et al., while the content with a structured layout, the worksheet, had the largest mean radii of curvature [17]. To determine whether these average radii of curvature were statistically different, a repeated-measure one-way ANOVA test was performed at a 0.05 significance level. Despite the observation, an analysis of the optimal radii of curvature showed that the mean difference among the six content types was not significant \( F(5,174) = 1.62; p = .16 \). Moreover, the post hoc test did not show any statistical difference at all. Thus, the tendencies with regard to the content type and the preferred radii of curvature of the curved monitor were observed, and the differences were not statistically significant.

In fact, the standard deviation scores were noticeably large across all the content types. This implies that the curved panel will be generally preferred, but the ideal radius may differ depending on the preferences of the individual study participants.

In addition, the results of this experiment show that the users’ optimal monitor radius is significantly different from the optimal TV radius, which was determined by Park et al. to be 4000 mm [12]. It is plausible to assume that this difference may have occurred due to the size difference between the monitor and the TV, and also due to the distance between the user and the panel.

4. Experiment 2

The goal of Experiment 2 was to discover the usability of the curved display by comparing the reading performances of the flat and curved panels. The ambient lighting condition was identical to that in Experiment 1.

4.1. Method

The participants of Experiment 1 were the same as those of Experiment 2. The experiment room was lit with 6500 K, and the illuminance was 600 lx. Under this illumination, the luminance reflected from a white area in the content image was measured as 77.40 cd/m². The participants were seated at a 60 cm distance from the bendable display panel as 60 cm is reportedly the average distance between the eyes and the display in the office environment [22]. Before beginning the experiment, a sufficient explanation of the experiment procedure was provided to the participants, after which they were guided in practicing how to manage the bendable display panel until they were adept at it.

The participants were asked to read the texts displayed on both the flat and curved panels. They were told to inform the researchers when they have finished reading. An experimenter attached one of the text contents to the panel, and the participants were instructed to pull or push the bar handle when they found an optimal radius of curvature for reading the given text contents. When the participants found their most preferred curvature, the radius was recorded by the experimenter, and when they had finished reading the texts on the preferred curved panel, the experimenter made the panel flat manually and instructed the participants to read the text on the flat panel. For each reading, different text contents were provided, and the text content variants were provided to the participants in random order. The reading sequence of the flat and curved panels was also randomly arranged. The time duration was measured in seconds.

4.2. Results of Experiment 2, and analyses thereof: usability of the curved display

When asked to choose the optimal radius of curvature, none chose a radius of curvature with a convex shape in any of the given tasks. Consequently, all the radius of curvature data can be considered the radii of curvature of the concave panel. Based on both the radius of curvature data and the reading duration, statistical analyses were performed.

The time duration data derived from Experiment 2 were transformed into ratio data to eliminate the individual differences in reading speed. The time duration data for the flat panel were designated as 1, and the ratio of the time duration for the curved panel was computed. Based on the transformed ratio data, the average ratio of reading the text on a curved panel was calculated as
Figure 3. A comparison of ratios of time spent to read 2500 letters on curved panel (the time spent to read 2500 letters on flat panel was 1), N = 30.

0.93, with a standard deviation of 0.15 (see Figure 3). This indicates that the participants spent less time reading the 2500 Korean letters when the text was displayed on a curved panel. To determine the statistical difference, pairwise t-test was performed, and it yielded statistical significance \( t(29) = 2.46; p = .02 \). Therefore, it can be concluded that the curved panel offered better reading performance than the flat panel. Then the benefits that the study participants could derive when they watch content types other than text contents on the curved display were investigated.

5. General discussion

This research was conducted to determine the possible benefits of a curved display and the preference for it by conducting several user evaluations. For the two experiments performed in this study, a bendable display panel was devised to enable the participants to manipulate the radius of curvature of the panel in the experiments. It is interesting to note that the individual participants demonstrated different preferences with regard to the ideal radius of curvature; the empirical study also revealed, however, that the curved panel was preferred to the flat panel across all the contents, and that every participant read the given text faster when the panel was curved.

Although the differences in the optimal mean radius of curvature among the six monitor-related contents were not statistically significant in Experiment 1, it was observed that the optimal mean radii of curvature of the contents differed. In particular, the optimal mean radius of curvature of the 3D game had the smallest value (625.67 mm) among the six contents. This indicates that consumers need a sense of immersion when watching 3D game contents because the sense of a real environment is particularly effective for gamers [23]. On the contrary, the worksheet showed the biggest radius of curvature value (900.00 mm) among the six contents. This may mean that the participants had less need for an immersive view when viewing the worksheet, which contained only multiple lines and texts, possibly because they were used to reading documents on a flat panel or paper. Therefore, it will be reasonable to assume that the marketability will increase when the producers develop a monitor display with an appropriate optimal radius of curvature on particular content types, such as gaming monitors.

It is interesting to note that this study indicated a greater radius of curvature compared to that of the curved TVs in the market. This result may have been due to the display size, as mentioned in the study conducted by Suk et al., where they suggested that the optimal radius of curvature may increase as the display becomes larger [14]. In this regard, a smaller radius of curvature may be appropriate for the monitor display. From the perspective of consumer adaptation, however, it will be difficult to directly apply the radius of curvature that resulted from the experiments performed in this study. It is important to note that in the past, consumers felt awkward with the change from the cathode ray tube (CRT) to the flat display given that the CRT display had a slightly convex shape. Although the study participants preferred the curved panel to its flat counterpart, a smaller radius of curvature should be preferentially applied to the display because today’s consumers are more used to watching from a flat display. In this context, it will be more appropriate to apply a gradual change until the radius of curvature resulting from this study is reached.

For further study, it is suggested that a supplementary study be conducted using more realistic stimuli referring to the range of optimal radii of curvature discovered from this study. As the contents on an actual monitor emit light, it should not be assumed that the results of this study will coincide with the results of a study to be carried out on an actual monitor, because the reflection issue is always a consideration [24–26]. As printed materials were used in the experiments in this study, it should be verified how the reflection of the images at the opposite ends of the screen will appear on the monitor when the proposed radius of curvature is applied. Such additional study will increase the precision and reliability of the results obtained in this study.

6. Conclusion

This study investigated the optimal radius of curvature for six types of content images. Preference for the curved
display to the flat display was found across all the types of content images. Most remarkably, when the usability of a curved monitor display was examined, it was found that people read text contents faster when viewing these on a curved display. The results of this study provide evidence that the curved display has the potential to open a new monitor market with its increased usability and the consumer preference for it.

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