Depth Perception of 3-D Images Displayed by Two Stereoscopic Displays at Different Depths

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Abstract

We studied a 3-D display that uses two stereoscopic displays at different depths and found that two same-shaped 3-D images displayed at different depths by the two stereoscopic displays were fused into one 3-D image when they were viewed as overlapping. We also found the perceived depth of the fused 3-D image depended on both the luminance ratio of the two 3-D images and their original perceived depths. As these depth fusions were observed under conditions where the distance between the original perceived depths of the two 3-D images was short, i.e., under ten percent of the distance between the observer and 3-D display, we observed it extending the distance between the original perceived depths of the two 3-D images. This paper presents results that show that for a long distance between their original perceived depths, two 3-D images did not fuse into one image. However, they were closer to each other than their original positions.

Introduction

Depth-fused 3-D (DFD) displays have recently been proposed as new kinds of 3-D displays [1, 2]. They are composed of only two 2-D displays at different depths. Two 2-D images displayed on the two 2-D displays are the same except for their luminances. When they are viewed as completely overlapping, the two are fused into one between the two displays. As the perceived depth of the fused image depends on the luminance ratio of the two images, 3-D images can be displayed by changing the luminance ratio according to the depth at each pixel.

We studied a new 3-D display that uses two stereoscopic displays instead of two 2-D displays in a DFD display and found that two 3-D images with the same shape displayed by the two stereoscopic displays were fused into one 3-D image when they were viewed as overlapping as is the case of a DFD display in which two 2-D images are fused [3].

As previous evaluations of depth fusion have been done under conditions where the distance between the original perceived depths of the 3-D images displayed by the front and back stereoscopic displays has been short, i.e., under ten percent of the distance between the observer and the screens of the 3-D display system, we evaluated this by extending the distance between the original perceived depths of the two 3-D images. This paper presents results that show that for a long distance between the original perceived depths of the two 3-D images, the two 3-D images were closer to each other than their original perceived depths but they did not fuse into one image unlike when the distance between their original perceived depths was short.

Configuration for Display System and Depth Fusion of 3-D Images

Figure 1 is a schematic of the display system we studied. The two stereoscopic displays are at different depths from the observer. Both display a 3-D image at different depths. z_F and z_B indicate the perceived positions in the z-direction of the 3-D images displayed by the front and back stereoscopic displays, respectively, when only one of them displays a 3-D image. We have called z_F and z_B the original perceived depths in this paper.

The perceived depth of the fused 3-D image on the new 3-D display depended on both the luminance ratio of the two 3-D images and their original perceived depths. Since the original perceived depth of each 3-D image depends on the parallax between the images for the left and right eyes displayed on each of the stereoscopic displays, the human visual system is considered to perceive 3-D images through both depth-fused 3-D perception and binocular parallax on stereoscopic displays.

The observations of depth fusion in our display system in the previous study were done for a relatively short distance between the original perceived depths, z_F and z_B (indicated by D in Fig. 1),

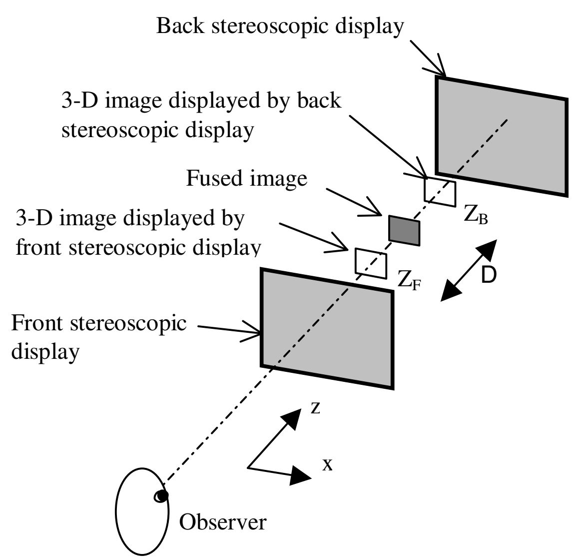

Figure 1. *Schematic of new 3-D display system. Z_F and Z_B indicate original perceived depth of 3-D images displayed by front and back stereoscopic display, respectively, which means perceived depth of 3-D image when each display shows 3-D image alone.*

which was under ten percent of the distance between the observer and the screens of the 3-D display system. It was very interesting to see whether two 3-D images displayed by the two stereoscopic displays would fuse into one image even when the two original perceived depths were at a long distance, i.e., over ten percent of the distance between the observer and the screens of the 3-D display system, because under such conditions it was considered to be difficult to apply a low-pass filter model that accurately presented the perception of a fused 3-D image on our 3-D display [4].

Subjective Tests

Subjective tests were done to clarify whether DFD perception occurred for a long distance between the original perceived depth of the 3-D image displayed by the front and back stereoscopic displays. Since the optical configuration in Fig. 1 is impossible in practice because the images are obstructed by the front display, we used the equivalent optical configuration in Fig. 2 instead. We used a 15" parallax-barrier-based stereoscopic display with 1024 (H) x 768 (V) pixels for each stereoscopic display. The distance between the observer and the midpoint between the two stereoscopic displays was 50 cm. The distance between the two stereoscopic displays was 2 cm. Under these conditions, cross talk between the left- and right-images did not occur for the two parallax-barrier-based stereoscopic displays used in this study. The two test patterns displayed on the front and back stereoscopic displays were the same white square patterns in Fig. 3. The pattern on the front screens was 2.4 cm (H) x 1.6 cm (V). The square pattern on the back display was slightly larger in proportion to the ratio of the distances between the observer and the front and back displays so that they completely overlapped from a single point of view. The distance between the original perceived depth of the pattern displayed by the front and back displays was changed as a experimental parameter by changing the distance between the patterns for the left and right eyes on each stereoscopic display.

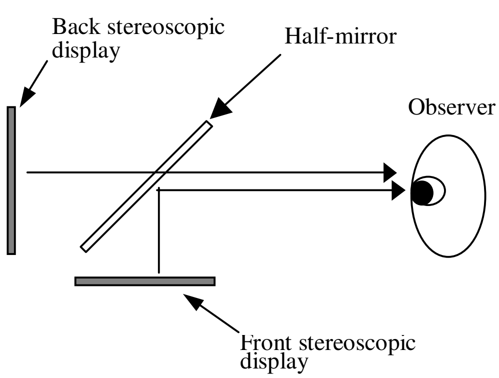

Figure 2. *Optical configuration used in experiment.*

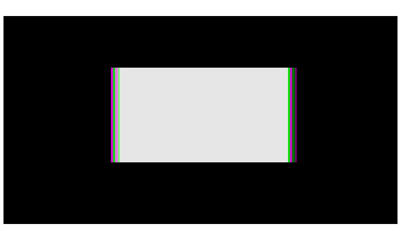

Figure 3. *Test pattern image.*

Subjective tests were done by five observers. They could all perceive depth through binocular parallax on the stereoscopic displays. They viewed the two square patterns in a way that seemed to overlap them most, although the two patterns did not overlap completely for both eyes. They answered if they could see them as two separate images at different depths or as a fused single image. The perceived depth of the fused image or each separate image was obtained by asking the observers to move a real object and stop it at the same depth as the fused image. The method for the subjective tests was basically the same as that in the previous study except for the distance between the original perceived depths of the front and back 3-D images.

Results and Discussion

Figure 4 plots the results for the subjective tests, where the y-axis indicates the depth and the origin of the y-axis indicates the midpoint between the screens for the front and back stereoscopic displays. The horizontal dotted lines indicate the depth of the screen position for the front and back stereoscopic displays. The x-axis indicates the distance between the original perceived depths of the front and back 3-D images. The original perceived depths of the front and back 3-D images are plotted by the oblique broken lines.

We can see from the figure that for distances over 5 cm between the original perceived depths of the two 3-D images, they did not fuse. However, both separate images were closer to each other than their original perceived depths whereas they fused for under distances of 3 cm between their original perceived depths. Moreover, we can see from the figure that for distances over 5 cm between their original perceived depths, the perceived depth of each 3-D image slightly decreased as the distance between their original perceived depths became longer although these distances were constant. Furthermore, we can see by comparing the three graphs in the figure that the perceived depths of the 3-D images that did not fuse did not have clear dependence on the luminance ratio of the two 3-D images, while the perceived depth of the fused image depended on the luminance ratio of the original front and back 3-D images. The range of the luminance ratio for these results was about 40 to 60 %, which was narrow. They might have dependence on the luminance ratio for larger or smaller luminance ratios than those in Fig. 4.

The results in Fig. 4 cannot be explained with the low-pass filter model that we applied to depth fusion in the 3-D display system in our previous study [4]. According to the low-pass filter model, the human visual system cannot solve the binocular-matching problem for the pattern edges of two images overlapping at different depths. As a result, it only uses the low-spatial-frequency component to solve this binocular-matching problem. A filtered image reconstructed from the low-spatial-frequency component can only generate one vertical edge for one side of the pattern in each eye image, which results in a single disparity in the image. Contrary to conditions where the low-pass filter model could be applied, the distance between vertical edges for one side of the front and back patterns in each eye image were long in this study, so that the observer perceived the two edges clearly.

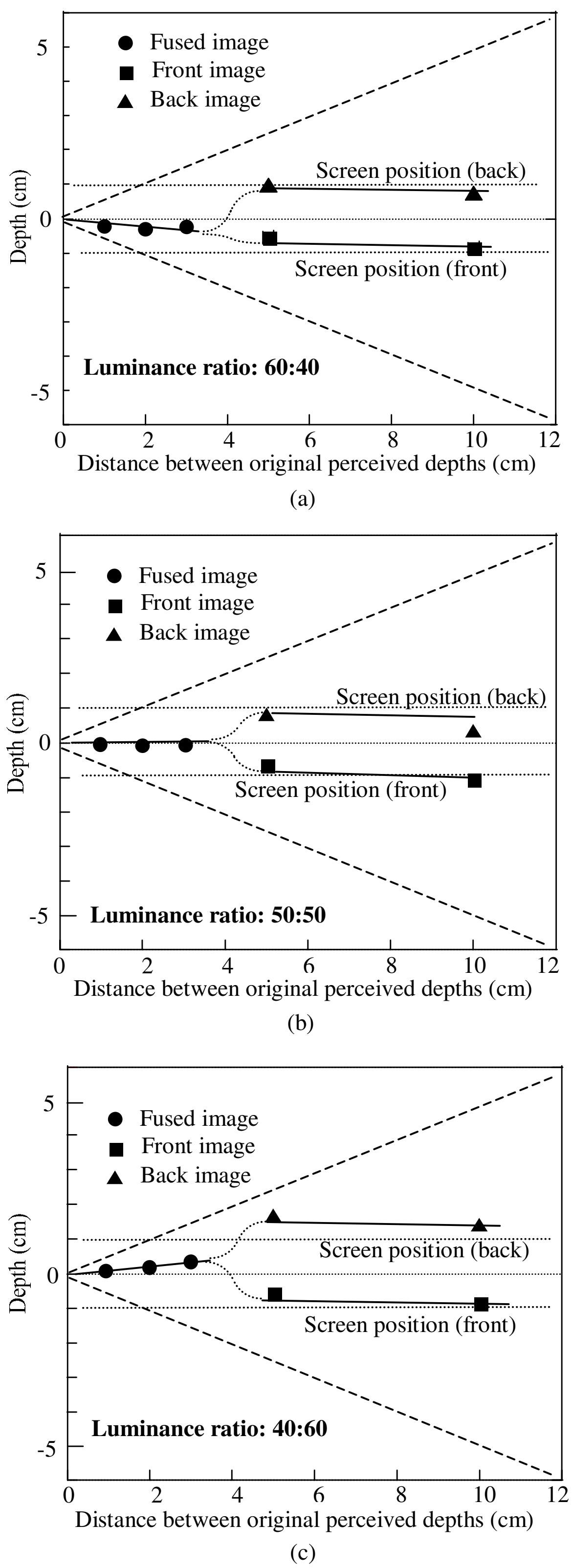

Figure 4. Results of subjective tests on perceived depth of 3-D images. Differences between three graphs are in luminance ratios of front and back 3-D images.

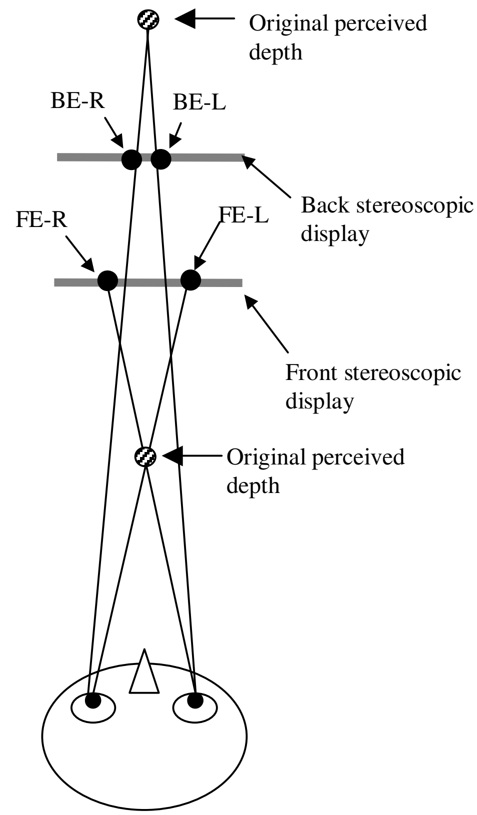

Figure 5. *Position of pattern edges for left and right eyes on stereoscopic display and perceived depth of 3-D image. FE-R and FE-L indicate pattern edges of images for right and left eyes displayed by front stereoscopic display. BE-R and BE-L indicate pattern edges of images for right and left eyes displayed by back stereoscopic display.*

The reason that the perceived depths for the front and back 3-D images differed from their original perceived depths has not yet been clarified. One possible reason is that when the human visual system undertakes binocular-matching, it may select the wrong pair of edges. That is, in Fig. 5, it might see BE-L and FE-L as the same edge, although they are the edges of different patterns. Although this mismatching model qualitatively explains the difference between the perceived depths of overlapping 3-D images and their original perceived depths, we need to quantitatively verify its validity.

Conclusion

We investigated the perceived depths of 3-D images displayed on two stereoscopic displays at different depths so that they overlapped. We clarified the following phenomena through subjective tests.

Under conditions where the distance between the original perceived depths of 3-D images displayed on the front and back stereoscopic displays was long; i.e., over 10 % of the distance between the observer and the screens of the 3-D display system, the two 3-D images did not fuse into one image, although they fused for a short distance between the original perceived depths of the two 3-D images. However, the perceived depths of the two separate 3-D images differed from their original perceived depths. They were closer to each other than their original perceived depths. One possible reason for this is that the human visual system may incorrectly match binocular matching. Although this could qualitatively explain the depth perception conducted in this study, quantitative verification of this hypothesis is needed in future work.

Acknowledgements

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Biography

Kazutake Uehira received his B.S. and M.S. degree in electronics in 1979 and 1981, respectively, and his Ph.D. degree in 1994, all from University of Osaka Prefecture, Osaka Japan. He joined NTT Electrical Communication Laboratories, Tokyo Japan, in 1981. Since then, he has been engaged in the research and development of display systems including 3-D displays and high-reality video communication systems. In 2001, he joined Kanagawa Institute of Technology as a professor.