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Stereo display with time-multiplexed focal adjustment

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Abstract

In stereo displays, binocular disparity creates a striking impression of depth. However, such displays present focus cues—blur and accommodation—that specify a different depth than disparity, thereby causing a conflict. This conflict causes several problems including misperception of the 3D layout, difficulty fusing binocular images, and visual fatigue. To address these problems, we developed a display that preserves the advantages of conventional stereo displays, while presenting correct or nearly correct focus cues. In our new stereo display each eye views a display through a lens that switches between four focal distances at very high rate. The switches are synchronized to the display, so focal distance and the distance being simulated on the display are consistent or nearly consistent with one another. Focus cues for points in-between the four focal planes are simulated by using a depth-weighted blending technique. We will describe the design of the new display, discuss the retinal images it forms under various conditions, and describe an experiment that illustrates the effectiveness of the display in maximizing visual performance while minimizing visual fatigue.

Keywords

Stereo display; volumetric display; focus cues; accommodation; blur; 3D; applied optics; variable power lens; birefringence; depth perception

1. INTRODUCTION

It is an exciting time for stereo display technology. There has been a steady influx of new designs for stereo displays including autostereoscopic desktop displays¹ head-mounted displays², 3D cinema projectors³, medical visualization devices⁴, and more. These displays show the left and right eyes different projections of the scene stimulating binocular disparities consistent with a 3D scene. There are, however, well-documented problems⁵. One problem is that conventional stereo displays present incorrect focus information, and we will devote the remainder of this paper to this problem.

In the real world, images arrive at the eyes with varying disparity, so as the viewer looks from one point to another, he/she must adjust the vergence of the eyes (the angle between the lines of sight). The distance at which the lines of sight intersect is the *vergence distance*. Real images also occur with different focal distances (the distance to which the eyes must focus, or accommodate, to sharpen the retinal image). Vergence and accommodation are neurally coupled: changes in vergence drive corresponding changes in accommodation (vergence accommodation) and changes in accommodation drive corresponding changes in

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vergence (accommodative vergence)⁶. This vergence-accommodation coupling is advantageous because vergence and focal distances are highly correlated in natural viewing, as shown in Figure 1A.

In conventional stereo displays, images have disparity thereby stimulating changes in vergence, but focal distance remains fixed at the display distance. Thus, the natural correlation between vergence and accommodative distances is disrupted (Figure 1B). Because of the vergence-accommodation coupling, it can be quite challenging for the viewer to fuse and focus a stimulus simultaneously; if accommodation is accurate, he/she will see the object clearly but might see two images (diplopia); if vergence is accurate, the viewer will see one fused object but it might be blurred. In addition to the difficulty of generating images that a viewer can see clearly and fuse, the vergence-focal conflicts that arise in conventional stereo displays may cause perceptual distortions and visual fatigue. To minimize these problems, we developed a stereo display that presents the standard 3D depth cues as well as any conventional display while also presenting correct or nearly correct focus cues. The control of the focal distance is made possible by a lens that can change focal power at a rate of 1KHz or higher. By placing the variable-power lens in front of the eye, we can adjust the lens to make the focal distance consistent with the simulated distance of an object even though the display screen is a fixed distance from the viewer. We synchronize the lens to the graphic display such that each depth region in the simulated scene is presented when the lens is in the appropriate state. In this way, we construct a temporally multiplexed image with correct or nearly correct focus cues.

1.1 Prior Work

The need to minimize the vergence-focal conflict has motivated the design and construction of several novel volumetric displays. These displays work by creating point sources of light at the surface of a virtual 3D object. In one display a rotating screen is synchronized with a projector so that the screen sweeps out a volume, and the 2D image pixels become 3D voxels⁷. In another, a stack of liquid-crystal panels produce a volumetric display with no moving parts⁸. The problem with these approaches is that they use additive omni-directional voxels and, as a consequence, they cannot correctly present many view-dependent effects, like occlusion and specularities. Such effects are crucial to depth perception⁹, so the inability of these displays to handle them correctly is a serious shortcoming.

Conventional stereo displays, when viewed from the correct position, present nearly all cues correctly with the notable exception of focus cues. Focus cues are by themselves relatively weak cues to depth, but they affect visual percepts^{10, 11}, performance¹¹, and fatigue^{11, 12, 13, 14} in a variety of ways. Our approach is to retain the useful features of conventional stereo displays while producing correct or nearly correct focus cues.

2. A TIME-MULTIPLEXED VOLUMETRIC STEREO DISPLAY

2.1 Overview of the approach

Our display is based on the principle of producing a geometrically correct image for each eye and using a switchable lens to adjust the focal distance associated with each part of the simulated scene appropriately so that the focus information is consistent or nearly consistent with the simulated depth. The human visual system has very high spatial resolution and stereo acuity, so it is critically important to present high-resolution images to each eye¹⁵. The resolution requirements for changes in focus cues are fortunately relatively low because the depth of field of human vision is roughly ± 0.3 diopters¹⁶ (where a diopter is the reciprocal of distance in meters and is abbreviated D). We built a display with ~ 0.6 D spacing between four focal planes; the workspace therefore encompassed ~ 1.8 D.

We divide the simulated scene into different distance ranges and illuminate those regions on the display only when the lens is at the appropriate focal power. By running through the four focal states, we sweep out the full scene every four frames. The fast, switchable lens is the innovation that makes this display possible.

2.2 Correct or nearly correct focus cues generated with switchable lens system

The switchable lens combines the principle of a fixed birefringence optic with the adaptive control properties of liquid crystals. A lens-shaped object made of transparent birefringent material has two focal lengths depending on the orientation of the polarization of the incoming light: one corresponds to the ordinary refractive index and the other to the extraordinary index¹⁸. Our birefringent material is calcite, which is transparent and can be machined into a desired shape. The incident unpolarized light from a display first passes through a linear polarizer, and then through a ferroelectric liquid-crystal (FLC) polarization rotator. The FLC acts as a switchable half-wave plate and, when oriented 45° to the plane of polarization, enables the incident polarization state to be rapidly modulated (240 μs switching time) between 0 and 90°. Thus, we can select one of two refractive indices, and thereby one of two focal powers, by applying the appropriate voltage to the FLC. We place lenses and FLCs in series to produce additional focal states; with N lenses, 2^N states are achievable.

Figure 2 illustrates a system of two lenses and FLCs for each eye. FLC1 is modulated at twice the frequency of FLC2, which enables the sequential addressing of all four combinations of polarization to the two lenses. The result is a four-state switchable lens. In our display, there is one four-state lens for each eye, thereby producing a stereo display with correct or nearly correct focus cues.

Halbo Optics, Ltd. manufactured two pairs of plano-convex calcite lenses 20 mm in diameter with an anti-reflection coating. The convex surfaces have radii of curvature of 143.3 and 286.7 mm, so the four focal powers are 5.09, 5.69, 6.29, and 6.89 D. Note that those values are separated by 0.60 D. An additional pair of static glass lenses can be inserted in the light path to move the workspace to a different range of distances. The optics were mounted in custom assemblies (Figure 3B) along with a pair of linear polarizers (Meadowlark Optics) and two pairs of FLC polarization rotators (LV2500, DisplayTech). Front-silvered prisms were placed in the light path to reflect light from two CRT displays through the lens systems and into the viewer's eyes (Figure 3A).

2.3 Synchronization with CRT displays

The FLCs are driven sequentially with appropriate electronic signals, and synchronized to the vertical refresh of the CRTs. The switching time of the FLCs is very short so the transition between focal powers can be made during the vertical retrace period (i.e. the period between a vertical synch pulse and the start of a visible frame trace). On each display refresh, the lens is switched to a new focal state; with four refreshes, the lens has gone through the four available states. To synchronize the state of the lenses to that of the corresponding display, we presented a small rectangle in the corner of the display on the first frame of the sequence and detected it with a photodiode. The detected signal reset the custom electronics whose output drove the lens switches.

As the lenses cycle through the four focal states, the CRTs present the parts of the simulated scene whose distances are consistent with the lenses' current focal state (Figure 4). When the distance of a simulated object corresponds to one of the available focal distances, pixels representing the object are illuminated only on frames in which the lens is set to the appropriate focal distance. When the distance of a simulated object falls in-between

available focal distances, we use an intensity allocation technique called *depth-weighted blending*¹⁸. The simulated distance D_s is expressed in diopters, and the pixel's intensity I_s is distributed to the nearer and farther planes respectively as I_n and I_f according to the formula:

$$I_n = \left[1 - \frac{(D_n - D_s)}{(D_n - D_f)} \right] I_s, \quad I_f = \left[\frac{(D_n - D_s)}{(D_n - D_f)} \right] I_s \quad (1)$$

where D_n and D_f are respectively the dioptric distances of the nearer and farther of the two bracketing focal planes. Thus, pixels representing an object at the dioptric midpoint between two focal planes are illuminated with half intensity on the two planes. The pixels for the two planes are aligned at the eye, so they sum in the retinal image to form an approximation of the image that would occur when viewing a real object at that distance. For an object closer to one of the display planes, then intensities are suitably modulated to give more weight to the plane closest to the object. As Equations 1 show, the sum of the intensities remains constant at all simulated distances; i.e. $I_n + I_f = I_s$ for all D_s . Depth-weighted blending is crucial for avoiding discontinuous changes in the retinal image as simulated distance changes¹⁸. The effectiveness of our presentation technique is discussed further in Section 3.

2.4 Display and computer hardware

We performed the graphics computations in Matlab using Psychtoolbox OpenGL function calls¹⁹. The software runs on a Quad Core Mac Pro (2.8 GHz) with an NVIDIA 8800GT dual-head graphics card. The displays are Iiyama HM204DT 22-inch CRTs. We run the displays at 180 Hz, which allows us to cycle through the four focal states at 45 Hz. At that frame rate, the display resolution is 800×600, which yields a pixel width of 2.4 arcmin (Nyquist frequency of 12.5 cycles/deg). The refresh rate is essentially as high as possible with CRTs because at higher rates phosphor persistence introduces “ghosting” between focal states. LCOS, DLP, and OLED displays could provide much higher frame rates and somewhat better resolution.

3. SYSTEM EVALUATION

3.1 Retinal-image analysis

It is crucial for a display to present high-quality images. Many variable-focal lenses use Fresnel elements and, as a consequence, have reduced image quality. LC Fresnel lenses share the same problem as conventional fixed Fresnel lenses of being essentially a form of diffraction grating. This means they can work well at a single wavelength but have severe chromatic effects²⁰. Our lenses have high optical quality equivalent to that of glass lenses.

It is also important to consider the formation of retinal images as simulated distance is changed. Retinal images are not only affected by the properties of the stimulus, but also by the viewer's optical aberrations, pupil size, and accommodative state. An effective way to quantify retinal-image quality is to determine contrast attenuation for sinusoidal luminance gratings. Figure 5 plots contrast ratios—retinal-image contrast divided by incident contrast—for various viewing conditions. The rows represent different display techniques: natural viewing, a conventional stereo display, and the switchable-lens stereo display. The columns represent stimulus spatial frequencies of 4, 8, and 16 cycles/deg (for reference, the spatial frequency to which the visual system is most sensitive is ~4 cycles/deg²¹; the highest frequency that can be seen at 100% contrast is 40–50 cycles/deg²¹; the most important range of spatial frequencies for driving accommodation and determining perceived blur is 4–8 cycles/deg^{22, 23}). In each panel, the abscissa represents simulated or real distance in

diopters, and the ordinate represents different accommodative states in diopters. Brightness represents the contrast ratio: higher values indicating larger ratios.

The top row of Figure 5 shows contrast ratios for natural viewing of real stimuli. When the stimulus distance is 1.5 D, the viewer produces the highest contrast in the retinal image by accommodating to 1.5 D. Under- and over-accommodation produce blur, which is manifest by reduced retinal contrast. Notice that the contrast reduction associated with accommodative errors is less at 4 cycles/deg and greater at 16 cycles/deg²⁴. Nonetheless, retinal contrast is always maximized by accommodating to the simulated distance. The middle row shows the results for a conventional stereo display at a fixed distance of 50 cm (2D). Now retinal contrast is maximized (i.e., blur is minimized) by accommodating to 2 D for all simulated distances. To see clearly, the viewer must therefore hold accommodation fixed, and this requires counteracting the natural coupling between vergence and accommodation. The bottom row shows the results for our switchable lens display. With four focal planes separated by 0.54, and 0.68 D intervals, the workspace spans 1.75 D. Within this space, the retinal-image contrasts produced by our display are quite similar to the contrasts produced by natural viewing, particularly at 4 and 8 cycles/deg. It is particularly important to note that for a stimulus at the midpoint of two focal planes (e.g. 1.62 D, retinal contrast is maximized by adjusting accommodation to the simulated distance (1.62 D) despite the fact that there is no focal plane at that distance. Thus, ~0.6 D spacing coupled with depth-weighted blending provides a quite reasonable approximation to natural viewing. At 16 cycles/deg, the approximation is less accurate.

Stimuli in our display appear realistic even when the simulated distance is in-between available focal planes. Figure 5 contains a demonstration of the retinal image formed by a coin (a U.S. quarter) at a distance of 1 m (1 D). (Note that distance falls midway between the Far and Far-Mid planes of our display.) We convolved the coin image with the point-spread functions appropriate for a human viewing a real coin and coins presented in different displays. At the viewing distance of the simulation, the “CALIFORNIA” text is approximately the size of a 20/20 letter on a Snellen acuity chart. In the simulations of natural viewing, a conventional display, and the switchable-lens display, we assume that the accommodative response (i.e. the distance to which the eye was focused) was equal to the vergence distance (equivalent to the simulated distance). In natural viewing, the retinal image is reasonably sharp because accommodation is appropriate for the viewing distance. The image is much blurrier in the conventional display because accommodation is assumed to be consistent with simulated distance rather than focal distance. The coin’s image in the switchable-lens display is a reasonable approximation to the image with natural viewing. This demonstrates the effectiveness of our technique for simulating images in-between focal planes by the use of depth-weighted blending.

3.2 Experiment: Time to fusion

For a stereo display to be useful, the viewer must be able to fuse the displayed stimuli binocularly and thereby appreciate the simulated depth. In conventional stereo displays, achieving binocular fusion while maintaining sharply focused retinal images can be problematic. To quantify fusion and focusing difficulty, we measured the time needed for viewers to fuse a stereogram under various accommodative and vergence demands.

3.2.1 Observers—Eight subjects, 22–26 years of age, participated. All had normal stereopsis as assessed by a standard clinic test. All used their normal optical correction during the experiments, and all were naïve to the experimental hypothesis.

3.2.2 Method—Trials began with the presentation of a fixation cross at the center of the viewing frustum. The cross was a depth-weighted blend simulating a focal distance of 1.62 D (midway between the Mid-Near and Far-Mid planes). The fixation cross was displayed for $2 (\pm 0.6)$ sec and was then replaced by a random-dot stereogram that depicted a sinusoidal corrugation in depth. The vergence distance of the stereogram stimulus was randomly assigned to one of three values: the same distance as the fixation cross, the near focal plane, or the far focal plane. The focal distance was also randomly assigned to one of those three values. The variable of main interest, however, was the relationship between the vergence and focal distances. Figure 6A shows the nine combinations of vergence and focal distance of the test stimulus. Some combinations involved changes in focal and vergence distance that were consistent with one another, as they are in real-world viewing. Some involved changes in vergence distance without changes in focal distance; this mimics the situation with a conventional stereo display. Some combinations involved changes in focal distance without changes in vergence distance and some others involved opposing changes in focal and vergence distance. Each observer experienced each of the nine combinations roughly equal numbers of times.

The observers' task was to identify the orientation of the sinusoidal corrugations in the stereogram; they were either $+15^\circ$ or -15° from horizontal. The corrugation orientation could not be perceived unless the observer verged quite accurately. They also had to focus reasonably accurately. Using a psychophysical staircase technique, we adjusted the stimulus duration to find the shortest value for which the observer could correctly identify the corrugation orientation 75% of the time.

3.2.3 Results—The results are plotted in Figure 6B; the data are from five of the eight observers because three could not perform the task reliably in many of the conditions. The minimum duration required to perform the task is plotted as a function of the vergence and focal distances. The shortest minimum duration occurred when the test stimulus appeared at the same vergence and focal distance as the initial fixation cross. When vergence and/or focal distance changed, the minimum duration increased. The effect of the change in vergence distance was clearly greater than the effect of the change in focal distance. This is not surprising because accurate vergence is more critical than accurate focus for stereopsis. Indeed, the change in focal distance was only ~ 0.9 D, which is not significantly greater than the depth of focus of human vision^{16, 24}. We would presumably have seen a larger effect of the change in focal distance if we had presented a larger dioptric change. Nonetheless, there was a consistent effect of the change in focus distance: when observers had to accommodate to a change in focal distance, the minimum time to perform the task increased.

4. DISCUSSION & CONCLUSIONS

The switchable-lens stereo display produces correct or nearly correct focus cues across its 1.75 D workspace. Our analysis of retinal-image formation shows that depth-weighted blending is effective at producing retinal images that are reasonable approximations to those formed in natural viewing. The approximation is excellent at 8 cycles/deg, which corresponds roughly to the spatial-frequency range that is most important for driving accommodation and determining the perception of blur^{22, 25}. At higher spatial frequencies, the approximation is less accurate, but given the low sensitivity of human vision to high frequencies, it is unclear whether this is important to perceived image quality and other aspects of visual performance. In the time-to-fusion experiment, we showed that correct or nearly correct focus cues aid binocular fusion. We also demonstrated that the virtual focal planes formed with depth weighted blending do not disrupt the fusion of stereograms.

Our display offers a promising approach for reducing vergence-accommodation conflicts and thereby improving visual performance^{10, 11, 18} while reducing visual fatigue¹¹. The design is extensible so more veridical image formation will be possible as higher-resolution and faster display technologies become available. We will be refining the system to make it more robust to viewer misalignment. We will also investigate miniaturizing the lens system so that it could be head-mounted or worn as spectacles.

The technology underlying the expanded use of stereo displays has been advancing rapidly. There has been, however, an under-appreciation of how the limits and requirements of the visual system affect perception, performance, and fatigue with stereo displays. For example, the conflict between simulated distance and focus cues has several consequences on the viewer and these consequences are frequently ignored. The development of stereo displays that minimize the conflict is an important step in matching the display technology to the viewer.

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Figure 1. Diagram of stimuli in the real world and a conventional stereo display. A) Real stimuli provide consistent vergence and focal distances. B) In conventional stereo displays, the focal distance is the distance to the display surface; thus, focal distance and vergence distance are generally inconsistent with one another.

Figure 2.

Schematic of the switchable lens assembly. Between each eye and its respective display, there is a lens system consisting of a static glass lens (A) to adjust overall focal power, a linear polarizer (B), ferroelectric liquid crystal 1 (C) to modulate the polarization angle of the light approaching the first birefringent lens (D), and ferroelectric liquid crystal 2 (E) to modulate the polarization angle of the light approaching the second birefringent lens (F).

Figure 3. Time-multiplexed stereo display. A) Photograph of the apparatus showing the haploscopic arrangement of the lens system, mirror prisms, and CRTs. B) Close up of the lens systems. C) Top view of the light path from the CRT through the lens system to one eye. The shaded area is the workspace in which we can present approximately correct focus cues. With a static glass lens in the system, the four focal planes are Far (133 cm; 0.75 D), Far-Mid (78 cm; 1.28 D), Mid-Near (51 cm; 1.96 D), and Near (40 cm; 2.50 D). The dioptric distance between the focal planes differs slightly from the theoretical values because of the positioning of the lenses.

Figure 4.

Lens state and pixel illumination over time. The workspace is the trapezoid bounded by the Near and Far planes and the diagonals on the left and right. For each simulated distance, pixels are illuminated according to their distance in diopters from an available focal plane. When the simulated distance corresponds to an available focal plane, pixels are illuminated at that plane (which of course corresponds to one time segment in the overall frame of the display); this situation is represented by dark red. When the simulated distance falls in-between available planes, pixels are illuminated on both planes (i.e. at the appropriate times in the overall frame) with their intensity corresponding to the relative dioptric distance of the simulated object from the planes (Equations 1); we call this intensity allocation technique depth-weighted blending¹⁸ and it is represented by the gradient of red.

Figure 5.

Retinal-image formation for different viewing conditions. In the main part of the figure, the columns represent the imaging of sinusoidal gratings of different spatial frequencies: 4, 8, and 16 cycles/deg (cpd) from left to right. The rows represent different viewing conditions: natural viewing, conventional stereo display, and switchable-lens stereo display from top to bottom. Each panel shows the contrast ratio (retinal-image contrast divided by stimulus contrast) as a function of simulated distance in diopters (abscissa) and accommodative state in diopters (ordinate). Brightness represents contrast ratio, higher values indicating greater ratios. The contrast ratios were calculated for author DMH's left eye with a 4 mm pupil diameter. The gray arrows in the left column mark the focal distances of the focal planes. To the right are images of coins (U.S. quarters). The upper image of the coin is unblurred. The next three images are simulations of the coin image at the retina for the viewing conditions represented by the gray dots in the right column of panels. These images were produced by convolving the appropriate point-spread function with the coin image. The point-spread functions were calculated from measurements of DMH's left eye with a 4 mm pupil. The optics of the eye were measured and analyzed with tools developed by Austin Roorda at UC Berkeley. From top to bottom, the resulting images represent the blurred retinal images in natural viewing, with a conventional stereo display, and with the switchable lens display.

Figure 6.

The experimental conditions and results. A: Vergence distance (defined by disparity) is plotted on the X-axis, and focal distance on the Y-axis. The small diagrams are top views of the different conditions. The eyes' lines of sight intersect at the vergence distance. The blue cones denote the focal distance. The pink and blue cones from the middle row signify that the focal stimulus is formed with a depth-weighted blend from the two central image planes. The gray region denotes the cues-consistent stimuli where the focal and vergence distance are equal. The individual diagrams depict the various viewing conditions. The black lines are the different focal planes of the display. The dashed black line is the virtual focal distance produced by a 50/50 blend from the two central image planes. This is shown in the small figures as blue light cone coming from the far-mid focal plane, and pink light cone coming from the mid-near focal plane. The diagonal bar highlights the consistent stimuli. The stimuli from the middle row are our emulation of a conventional stereo display. For these stimuli, light was emitted from the virtual focal plane in the center of the display. B: The minimum time needed to judge the stereogram correctly 75% of the time is plotted as a function of vergence distance and focal distance. The height of the bars is the log-Euclidean mean for the observers. The central bar represents the stimulus that appeared at the same vergence distance and focal distance as the fixation cross. The bars at the lower right and upper left correspond to the opposing vergence-focal changes. The bars at the lower left and upper right are the trials in which the vergence-focal change was consistent.