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Near-correct ocular accommodation responses to a 3d display, using multiple image planes and depth filtering.

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Abstract

Conventional stereo displays provide incorrect focus cues because the image is presented on a single surface. This is known to cause a number of aversive symptoms in users, including fatigue and discomfort. Multiple-focal-plane displays have been proposed as a solution to this problem. In principle, a continuous range of focal distances can be simulated by distributing image intensity across multiple focal planes - a technique referred to as depth filtering. Here we evaluate this approach by measuring the focusing responses of the human eye (accommodation) to focal distances simulated in this way. We found that changes in simulated distance led to an appropriate change in accommodation. Moreover, responses could not be distinguished from those to real focal distances. We conclude that depth-filtered images can stimulate the eye's focusing response appropriately, and so could offer significant improvements to stereo displays.

Categories and Subject Descriptors (according to ACM CCS): I.3.1 [Computer Graphics]: Three-dimensional displays

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1. Introduction

In conventional stereoscopic displays the focal distance to points in the simulated scene is inconsistent with the depicted scene because the light comes from a single display surface. This causes two problems. First, focus cues to depth, from the eyes' focusing response (accommodation), and the gradient of retinal blur, specify the display surface rather than the portrayed scene. This can lead to distortions in perceived depth [WAEB05, HGAB08]. Second, there is typically a mismatch between the demand on accommodation and vergence eye movements. These two responses are normally coupled, and accommodating to one distance, while converging at another, has been shown to cause discomfort, fatigue, difficulty fusing stereoscopic images, and reduced stereo acuity [AWGB04, Wop95, WMW97, UH08, HGAB08]. Presenting correct focus cues should therefore lead to significant improvements over conventional stereoscopic displays. Multiple-focal-plane displays appear to be a promising approach to achieving this [AWGB04]. It has been proposed that continuous variations in focal distance might be achieved by presenting a weighted "blend" of image intensities at more than one focal plane–referred to as depth-filtering [AWGB04]. Here we evaluate this directly by measuring the eye's accommodation response to depth-filtered images.

1.1. Related work

Following Rolland [RKG99], and Fakespace Labs [MB94], several groups have produced multiple-focal-plane displays, using either fixed optics [AWGB04], or adaptive optics approaches [She05, LCH08, HHK*09]. Our work follows closely that of Akeley et al. [AWGB04], who developed a prototype display with three 'stacked' image planes for each eye, separated by $\frac{2}{3}$ dioptre (D) (dioptres are the reciprocal of metres), using mirrors and beamsplitters (see Figure 1).

A critical requirement of such displays is to approximate the continuous range of variation in focal distance in the real world. One approach is to place the image planes sufficiently close together that the human visual system cannot detect the

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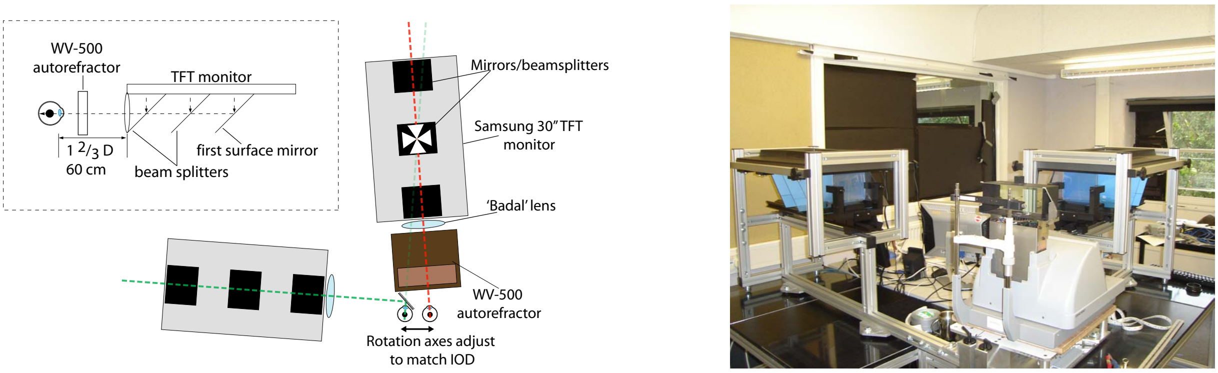

Figure 1: *Left panel. Plan view (main figure) schematic of our prototype display. Three discrete image planes can be placed at different focal distances from the observer (see inset side view), and the eye sees the sum of light energy from each plane. The left display is viewed via a first surface mirror at 45° to the line of sight. The right eye's display shows a cartoon example of the visual stimulus used in the evaluation study. Right panel. A photograph of the actual display.*

differences in focal distance. To do this, however, Rolland [RKG99] estimated that the image planes would need to be spaced $\frac{1}{7}$ D apart, and so approx. 20 image planes would be needed for a display with a working range of 30-200 cm. Such a display is likely impractical in terms of both hardware complexity, and the computational expense of rendering so many images.

Akeley et al. [AWGB04] proposed a solution that allows fewer, more widely spaced image planes. Instead of presenting each point in the image at only one focal plane, light energy is distributed across multiple planes. This is possible in their device because the eye sees a sum of superimposed images drawn at each plane (see Figure 1). According to this technique, referred to as depth filtering (see Figure 2), image intensity at each image plane is weighted according to the distance (in dioptres) of a point in the scene from that plane, determined along lines of sight. Psychophysical studies have shown that depth-filtered stimuli can reduce many of the problems described above [AWGB04, HGAB08]. Moreover, they may also stimulate 'correct' accommodation responses to distances between image planes. The eye focuses by maximising retinal image contrast (i.e. minimising blur) [SACS92]. Taking account of the optics of the human eye, Hoffman et al. [HGAB08] computed the retinal image contrast when viewing depth-filtered images, with an inter-plane separation of $\frac{2}{3}$D, and found that they provide a reasonable approximation to that generated by viewing equivalent real-world objects. However, accommodation responses to depth-filtered images have not previously been measured.

1.2. Contribution

Our goal is to determine whether depth-filtered images stimulate an appropriate accommodation response. If so, they offer the possibility of eliminating the problems caused by incorrect focus cues in 3d displays.

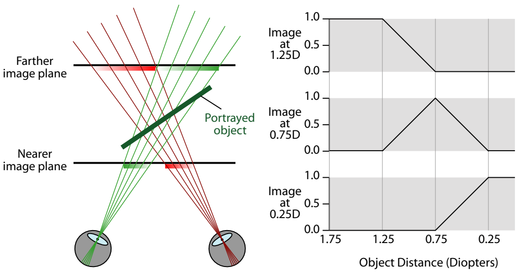

Figure 2: *The left panel illustrates how depth-filtering is carried out along lines of sight. The luminance energy of an image point is distributed across the two nearest image planes, according to the ratio of the dioptric distances from each plane. The right panel shows depth-filter functions for a three-plane display for image points at different depths and image planes at 1.25, 0.75 and 0.25D. The amount of blur due to defocus is proportional to the magnitude of defocus in diopters. Therefore the image planes need to be spaced equally in dioptric distance.*

We have constructed a 'test bed' multiple-focal-plane display (see Section 2), which allows us to examine this question in a well controlled manner. An important initial test is whether the simulated object stimulates a correct accommodative response when all other cues to distance (e.g., familiar size and vergence) are removed. As such, we test observers' accommodative responses to monocular stimuli that vary only in terms of their (real and simulated) focal distances. However, the display is also capable of presenting stereoscopic stimuli, and is designed as a general tool for vision research.

2. Prototype display

Our prototype display is schematized in Figure 1. Since we intend to use the display to address very specific questions, its design is optimised for certain properties, while compromising others. The display has separate views for the left and right eyes, presented on separate Samsung 30" TFT monitors (2560x1600 pixel resolution). Similar to the design used by Akeley et al. [AWGB04], each eye views the sum of light intensities from three image planes (Figure 1), created using a first-surface mirror (farthest plane) and two beamsplitters. In order to implement depth filtering correctly, we carefully calibrated the luminance response function of each image plane (measured at the eye's viewing position), allowing us to present a specified luminance at any plane.

Each eye views the image planes through a 15 x 12 cm lens with a focal length of $1\frac{2}{3}$D (60 cm). Observers are positioned using an individually calibrated bite-bar assembly. This fixes the viewpoint relative to the display, ensuring that images at different image planes are always correctly aligned. Moreover, it ensures that each eye is positioned along the centre line of the left or right display, at the focal length of the lens (the two display 'arms' can be moved apart to match different inter-ocular distances). This configuration is similar to that used in a Badal optometer. It limits the field of view (to the size of the lens), but it has useful properties for our purposes. Any object placed between the lens and its second (far) focal point has the same retinal size. This means that images can be drawn at the same size at each image plane, regardless of distance. The position of image planes is infinitely adjustable within the range of the display ($1\frac{2}{3}$ to 0 D). Note also that pixels in the display always have the same angular size at the retina, independent of distance.

3. Measurement of accommodation

We monitor the accommodative state of an observer's right eye using a Grand-Seiko WV-500 infrared video-based autorefractor. This device produces a measurement on a button press, but we sample the eye's accommodative state continuously (at 30 Hz) by analysing the video output using custom-written image analysis software (Matlab) (c.f. [WOCG04]).

4. Evaluation study

4.1. Observers

Five individuals participated in this experiment (age range: 22–32 years). Three of the observers had normal, uncorrected vision. Two wore corrections for myopia (-2.75 and -3D, respectively).

4.2. Stimulus and Procedure

The stimulus on each trial was a white Maltese cross (60 cd/m^2) on a dark background (0.27 cd/m^2)(see Figure 1), presented to the right eye only. Two viewing planes were placed $\frac{2}{3}$D apart, with the near plane at 1.33D from the observer. On a given trial, a stimulus was presented at one of seven focal distances, linearly spaced in dioptres. The nearest and farthest of these coincided with the image plane distances (1.33 and 0.67D), and so were 'real' focal distances (100% of the image intensity was at a single plane). The remaining five were at distances between the image planes, created using Akeley et al.'s [AWGB04] depth-filtering rule. The percentages of image intensity at the near plane were 100, 83, 67, 50, 33, 17, & 0%, respectively. The percentage image intensity at the far plane was $(100-l)$, where l is the image intensity drawn on the near plane.

Each observer viewed each simulated focal distance 20 times, for a period of five seconds. The order of focal distances was randomised. Observers were instructed to keep their view of the object as clear as possible for the duration of a trial. Accommodation measurements were taken from one second after stimulus onset until five seconds had elapsed (when the display was blanked). Each response was averaged over the four seconds of recorded time, and observer's responses were then averaged over the 20 repetitions.

4.3. Results

The accommodation responses to each stimulus, averaged across the five observers, are shown in Figure 3. There are two key points to note from this analysis. First, observers did not, on average, accommodate accurately to the real stimuli. This is a typical pattern of results, but is important because the responses to the depth-filtered stimuli must be interpreted relative to this performance level. Second, there was a clear, linear relationship between simulated distance and the accommodation response. That is, the depth-filtered stimuli produced appropriate mean accommodation responses to all distances between image planes.

Another important validation of the display is to confirm that variability in accommodation responses is comparable across real and simulated focal distances. If the stimulus to accommodation from depth-filtered images is poor, responses could be highly variable, perhaps even alternating between the two image planes (albeit with appropriate mean values). To examine this, we compared root-mean-square-deviation (RMSD) when viewing the real and depth-filtered images. The average RMSD for the real and simulated focal distances was 0.12D, ($sd = 0.033D$) and 0.14D ($sd = 0.042$D), respectively. A repeated-measures ANOVA indicated that there were no significant differences in RMSD value between an of the real or simulated focal distances ($F(6,24) = 0.89$, $p = 0.51$). Real and depth-filtered images therefore resulted in very similar accommodation responses.

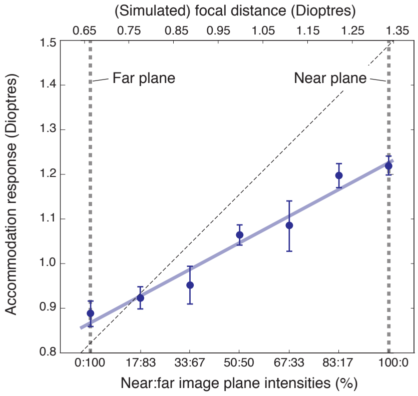

Figure 3: *Mean accommodation response as a function of simulated distance to the depth-filtered stimuli. The top x-axis shows (simulated) focal distance. The bottom x-axis shows the image intensity ratios for the near and far image planes. The vertical dashed lines indicate the positions of the image planes. The diagonal dashed line indicates perfect accommodation. The solid line shows the best-fit linear regression through the plotted data. Error bars represent* ±1 *SEM.*

5. Conclusions

We have shown that depth-filtered images, presented on a multiple-focal-plane display, can lead to continuous and appropriate accommodation responses to distances between image planes. This suggests that depth-filtered images do indeed provide near-correct accommodation cues. They should therefore significantly reduce the mismatch of demands on accommodation and vergence present in conventional 3d displays, leading to a reduction in fatigue, eye strain, and difficulty fusing stereoscopic images, as well as improving stereoscopic performance. Depth filtering is also a practical solution. Wide image-plane spacing allows the total number of image planes to be kept reasonably small while (according to our results) faithfully representing different focal distances.

Our display setup is a test-bed, and not a practical device for general use. However, it provides us with flexibility in terms of testing different combinations of focal distances, and the number of planes used in the display, and so can provide valuable "proof-of-concept" data on how the accommodation system responds to multiple-focal-plane displays, and depth-filtered images in general.

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