3D+2DTV: 3D Displays with No Ghosting for Viewers Without Glasses

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3D displays are increasingly popular in consumer and commercial applications. Many such displays show 3D images to viewers wearing special glasses, while showing an incomprehensible double image to viewers without glasses. We demonstrate a simple method that provides those with glasses a 3D experience, while viewers without glasses see a 2D image without artifacts.

In addition to separate left and right images in each frame, we add a third image, invisible to those with glasses. In the combined view seen by those without glasses, this cancels the right image, leaving only the left.

If the left and right images are of equal brightness, this approach results in low contrast for viewers without glasses. Allowing differential brightness between the left and right images improves 2D contrast. We observe experimentally that: (1) viewers without glasses prefer our 3D+2DTV to a standard 3DTV, (2) viewers with glasses maintain a strong 3D percept, even when one eye is significantly darker than the other, and (3) sequential-stereo display viewers with glasses experience a depth illusion caused by the Pulfrich effect, but it is small and innocuous.

Our technique is applicable to displays using either active shutter glasses or passive glasses. Our prototype uses active shutter glasses and a polarizer.

Categories and Subject Descriptors: I.3.1 [**Computer Graphics**]: Hardware Architecture—*Three-dimensional displays*

General Terms: Experimentation, Human Factors

Additional Key Words and Phrases: 3DTV, active shutter, Pulfrich effect

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1. INTRODUCTION

Stereoscopic displays provide different images to the viewer's right and left eyes to produce a three-dimensional (3D) percept. These displays' falling prices have caused them to grow from a niche product to mass market acceptance with applications in entertainment, medical imaging, and engineering visualization.

The most popular 3D display paradigm shows a pair of images on the same screen, intended for the viewers' left and right eyes. The lenses of special "stereo glasses" pass images to the correct eye. A viewer not wearing these glasses sees both images superimposed, creating a "ghosted" double image where two copies of objects appear overlayed (Figure 1(a)).

It is not always desirable to require that all viewers wear stereo glasses. They can be prohibitively expensive, or may interfere with other activities. It would be preferable to allow those not wearing stereo glasses to see a single, unghosted image (Figure 1(b)).

We accomplish simultaneous viewing of 3D and 2D images by replacing the pair of images (Left, Right) with a triplet (Left, Right, neither), where those wearing stereo glasses see the neither image with neither eye; only those *without* stereo glasses can see it. The neither image is the negative of the right image (Figure 1(c)) so that they cancel when superimposed, leaving only the left.

Unfortunately, this raises the minimum black level for viewers without stereo glasses, drastically decreasing the contrast ratio. This can be mitigated by reducing the brightness of the right image, α_R, to $\alpha_R < 100\%$, but maintaining the left's full brightness.

If this adjustment is small, the effect on the 3D experience of viewers with stereo glasses is negligible, but the increase in contrast ratio for viewers without glasses is also modest. If this reduction is larger, the improved contrast ratio for viewers without glasses will be significant, but if too large, the 3D experience of viewers with glasses will deteriorate. We conduct experiments identifying the acceptable range of α_R for both viewers with and without glasses, and find in Sections 5.1 and 5.2 that both are satisfied when $20\% \leq \alpha_R \leq 60\%$.

When viewers wearing stereo glasses see a brighter image with one eye than the other, they soon become accustomed to this and report an acceptable 3D experience. However, on a sequential-stereo display, they also report that horizontally moving objects appear at different depths than stationary or vertically moving objects with the same disparity. This small but measurable phenomenon is known as the "Pulfrich effect" and is similar to a time delay of several milliseconds in their perception of the darker image.

We conduct experiments to quantify this effect. We also measure a depth distortion of similar magnitude caused by the 8-millisecond delay between the left and right images in a 120Hz display. The distortion is small enough that it is typically ignored by 3D content creators. These two effects cancel each other when one eye's brightness is 40% that of the other eye.

The primary contribution of this article is a simple method to allow simultaneous viewing of 3D content by viewers with glasses, and 2D content by viewers without. We support this contribution

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(a) standard 3DTV (b) our 3D+2D TV (c) we Add a 3rd frame to cancel R

Fig. 1. (a) A typical glasses-based 3DTV shows a different image to each eye of viewers wearing stereo glasses, visible through the glasses at the bottom of the figure, while those without glasses see both images superimposed, visible directly on the screen at the top of the figure. (b) Our 3D+2DTV likewise shows a different image to each eye of viewers wearing stereo glasses, but shows only one of these images to those without glasses, removing the "ghosted" double image. (c) We accomplish this by displaying a 3rd image to those not wearing glasses that is not visible to those wearing glasses, canceling out one image of the stereo pair.

with experiments measuring: viewer preferences among 2D degradation options, viewer ability to perceive 3D when one eye is dimmed, and the magnitude of the pulfrich effect in this system. Lastly, we demonstrate a prototype built using two commercial 3D projectors.

2. RELATED WORK

Didyk et al. have also considered the problem of displaying a 3D image to a viewer wearing glasses while creating an acceptable 2D image for those without glasses, which they refer to as "backward compatible stereo" [Didyk et al. 2011, 2012]. They reduce the disparity between objects in the left and right images to a minimal threshold, preferentially retaining high-frequency components. Smaller disparities make the 2D composite image more acceptable to viewers without glasses, but a ghost image remains. Reducing disparity also improves tolerance to cross-talk, where images intended for 3D viewers' left and right eyes are not entirely hidden from the other eye [Siegel and Nagata 2000].

Anaglyph stereo uses two color channels with passive glasses to provide different views to each eye, while sacrificing color fidelity and showing a double image to viewers not wearing stereo glasses. The most common example uses red and cyan filters, but amber and blue filters have been used to reduce ghosting seen by viewers not wearing glasses [Sorensen 2004; Ramstad 2011].

Projection on an arbitrary textured object such as a brick wall is possible by adding a color cancelation term to the projected image [Grossberg et al. 2004; Grundhofer and Bimber 2008; Aliaga et al. 2012; Bimber et al. 2008]. We use the same principle, treating one of the stereo channels as a texture to be canceled. Projecting one image and neutralizing it with a compensation image may also be used to project coded patterns visible to high-speed cameras (but invisible to human observers whose eyes integrate the images at high projection frame rates), while simultaneously projecting a desired image [Raskar et al. 1998; Grundhöfer et al. 2007].

The undesirable ghosting seen by viewers not wearing stereo glasses is also avoided by autostereoscopic 3D displays that do not require special glasses. Several techniques have been used to create such displays [Dodgson 2005]. For example, a parallax barrier blocks light from reaching proscribed directions [Perlin et al. 2000], and a lenticular array bends light toward the desired direction [Matusik and Pfister 2004]. Autostereoscopic displays are generally more complex than glasses-based 3D displays and more expensive.

3. THE PULFRICH EFFECT

It will prove useful in Section 4.2 to allow subjects' left and right eyes to view images of unequal brightness. These subjects perceive accurate depths for stationary and vertically moving objects, but the depths they report for objects moving horizontally show a predictable distortion. This illusion, explored in Section 5.3 and known as the Pulfrich effect [Pulfrich 1922; Morgan and Thompson 1975], has been used to produce 3D effects on television by distributing tens of millions of paper glasses with one dark lens [Taub 2002]. Similar glasses are also used clinically to diagnose and treat depth perception impairments [Diaper 1997; Heron and Dutton 1989].

The Pulfrich effect is approximately linearly dependent on horizontal speed, and therefore consistent with a time delay in the darker image reaching the brain. While the undimmed eye sees the present world, the darkened eye sees the world as it was a few milliseconds ago. The undimmed eye sees a horizontally moving object's current position, but the darker eye its previous position, changing its apparent disparity, and thus its apparent depth [Dvorak 1872].

The human eye contains two types of light-sensing cells: rods and cones. Rods are far more sensitive to low light levels, and also have a longer latency than cones in transmitting images to the brain. The duplicity theory of vision holds that light-adapted vision involves chiefly the cones, while dark-adapted vision relies more on rods than cones, precipitating the delay in perception [Pollack 1968].

4. METHODS

A 3D+2D display is not restricted to a single stereo display technology. The key feature required is a third channel of information visible only to those not wearing glasses. In this section, we first discuss implementation options for an additional channel. We then discuss several options for the content of the third channel, which impacts the quality of the composite 2D image.

4.1 Implementing a Third Channel

Active-shutter displays show each image of the two-image frame packet sequentially, while the lenses of special stereo glasses become transparent or opaque in synchrony to block each eye from seeing images not intended for it. The temporal pattern can easily include more channels, to support our method, or uses such as additional stereo viewpoints [Agrawala et al. 1997; McDowall et al. 2001]. We expect our method to be most popular with active-shutter displays, whose stereo glasses are typically much more expensive

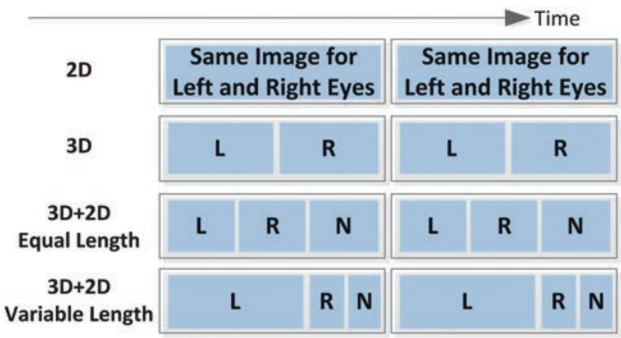


Fig. 2. We propose a new sequence of frames. (1st row) A traditional 2D display shows a single image to both eyes. (2nd row) Each frame in a traditional sequential-stereo display shows a distinct image to the left (L) and right (R) eyes of a viewer with glasses, while a viewer without glasses sees both images overlaid, with both eyes. (3rd row) Our 3D+2D display adds a third image (N) to each frame, shown to neither eye of the viewer with glasses, but seen by both eyes of a viewer without glasses. This third image is used to display the negative of the right image, leaving them a low-contrast version of the left image. (4th row) A 3D+2D display may allot more time to the left image to improve contrast, shortening the R and N images accordingly.

than passive stereo glasses, costing $100 or more. We have therefore addressed several issues, such as the Pulfrich effect and the utility of variable-length frames, that are specific to sequential-frame stereo displays. Figure 2 illustrates temporal patterns supporting our method for equal- and variable-length frames.

Several types of passive glasses may be used to build 3D displays. The most common glasses contain polarizing filters of orthogonal polarizations, while the display produces matching polarized images for each eye [Kim and Kim 2005]. An alternate option uses lenses with orthogonal spectral filters, each allowing different narrow bands of red, green, and blue wavelengths to pass [Jorke and Fritz 2006]. Passive stereo systems may produce the two images simultaneously with a pair of projectors, on interleaved rows of a flat-screen display, or sequentially with a projector and filter wheel. The third channel we require could be provided by a single method, such as a third mutually orthogonal spectral filter, or by combining methods, such as using polarization and spectral filters together to produce four orthogonal channels.

Our prototype combines polarization with active-shutter projectors.

4.2 Brightness of the Composite 2D Image

Our 3D+2D display shows three images each frame: L, R, and N. Viewers not wearing stereo glasses see only L, because N is chosen as the inverse of R such that N+R yields a uniform grey. The grey field raises the black level of the display: the brightness of the darkest pixel of the screen. If the three images are of equal brightness, the brightest pixel will be only twice as bright as the darkest pixel, a terrible contrast ratio. Allowing the L image to be brighter than the R and N images increases the contrast ratio. Several options are available to produce the N image, with different effects on contrast. We now analyze three possible options, depicted in Figure 3, and their impact, quantified in Figure 4.

Throughout, let L, R, and N be vectors of image pixels, containing all possible brightnesses. Let the functions $MAX(\cdot)$ and $MIN(\cdot)$ find the maximum or minimum element in the vector. Let $max_L = MAX(L)$ be the maximum possible brightness for any pixel in L, and similarly define max_R. Let $\alpha_R = max_R / max_L \leq 100\%$ refer to the brightness of the darker image R relative to L. Let $max_{2D} = MAX(L + R + N)$ be the brightness of the composite 2D image seen by viewers without glasses, and let its darkest possible pixel be $min_{2D} = MIN(L + R + N)$. Since N will be chosen to cancel

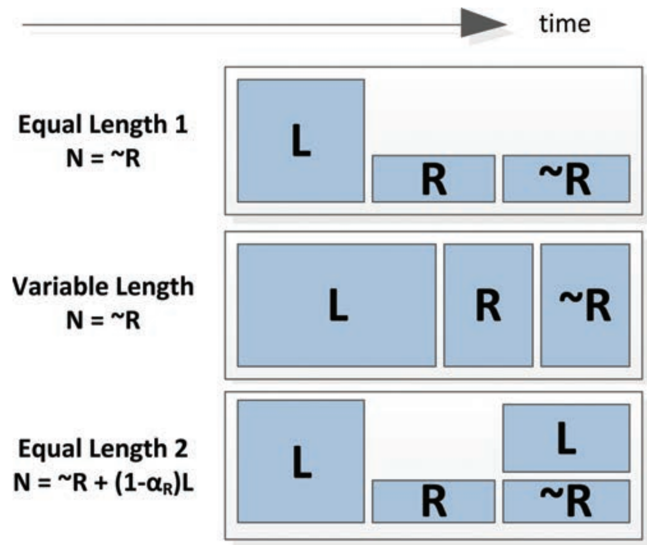


Fig. 3. (Top Row) When all three frames have equal length and N = ˜R, some available light is wasted. (Middle Row) Variable-length frames waste no light, improving contrast for 2D viewers. (Bottom Row) Equal-length frames may be improved by setting N $= \tilde{}R + (1 - \alpha_R) \cdot L$, wasting less light. For brevity we refer to the inverse of R as: ˜R $= (alpha_R \cdot max_L - R)$.

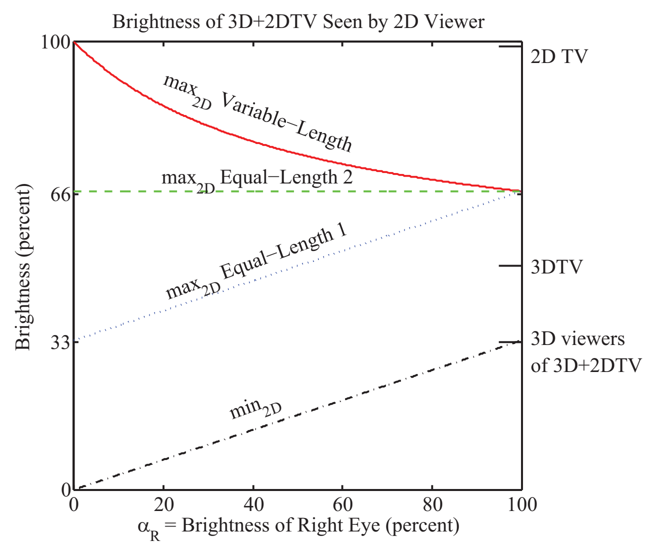


Fig. 4. The contrast between the brightest pixel (max_{2D}) and the darkest pixel (min_{2D}) of the composite 2D image seen by viewers not wearing stereo glasses improves when α_R is decreased. Variable-length frames produce a brighter 2D image than equal-length frames. For comparison, we have noted the brightness of a standard 2D TV, a standard 3D TV, and the 3D view of a 3D+2DTV.

out R, that is, $R + N = max_R$, we find that

$$min_{2D} = MIN(R + N) = max_R = \alpha_R \cdot max_L. \tag{1}$$

We now analyze how max_{2D} varies with α_R. First, in the simplest equal-length implementation of our technique, the three frames (L,R,N) are accorded equal time by the display. In this case, to darken the R and N images, α_R is reduced but the brightness of the L image max_L remains unchanged. To cancel R with N, we constrain N to: $R + N = max_R$, trivially achieved by setting $N = max_R - R = \alpha_R \cdot max_L - R$. Since the left frame is allotted one-third of the display's photons, $max_L = 1/3$, so the total brightness of the composite image is then

$$\begin{aligned} max_{2DE1} &= MAX(L + R + (\alpha_R \cdot max_L - R)) \\ &= max_L \cdot (1 + \alpha_R) \\ &= 1/3 + \alpha_R/3. \end{aligned} \tag{2}$$

Second, a variable-length sequential-stereo display may instead dim the R and N images by affording them a smaller fraction of the total time in comparison to the L image. For example, plasma and DLP displays typically form each frame from shorter microframes, which could be reapportioned unequally among the L, R, and N images. Alternatively, more whole frames may be devoted to L than to R or N. For example, the variable-length frame case of $\alpha_R = 50\%$ may be achieved with an equal-length frame sequence (L, L, R, N). In this case, darkening the R and N images allows a corresponding increase in the brightness of L. Thus, while $N = max_R - R$, as before, max_L is now constrained as

$$\begin{aligned} max_L &= 1 - 2 \cdot max_R \\ &= 1 - 2 \cdot \alpha_R \cdot max_L \\ &= 1/(1 + 2 \cdot \alpha_R). \end{aligned}$$

We thus find max_{2D} in this case as

$$\begin{aligned} max_{2DV} &= MAX((1 - 2 \cdot max_R) + R + (max_R - R)) \\ &= 1 - max R \\ &= 1 - \alpha_R \cdot max_L \\ &= 1 - \alpha_R \cdot 1/(1 + 2 \cdot \alpha_R) \\ &= (1 + \alpha_R)/(1 + 2 \cdot \alpha_R). \end{aligned} \tag{3}$$

Third, the equal-length implementation may be improved. Observe that, as initially described, with $\alpha_R < 100\%$ the N frame never shines with full brightness. Its unused brightness can be repurposed to duplicate L. Before, we had set $N = (max_R - R) = (\alpha_R \cdot max_L - R)$. Now, we add L in the unused portion of N.

$$N = (\alpha_R \cdot max_L - R) + (1 - \alpha_R) \cdot L$$

With $max_L = 1/3$ as before, the brightness of the composite image in this case is

$$\begin{aligned} max_{2DE2} &= MAX(L + R + (\alpha_R \cdot max_L - R) \\ &\quad + (1 - \alpha_R) \cdot L) \\ &= max_L + (\alpha_R \cdot max_L) \\ &\quad + (1 - \alpha_R) \cdot max_L \\ &= 2 \cdot max_L \\ &= 2/3. \end{aligned} \tag{4}$$

This constant brightness falls roughly halfway between the two simpler implementations, as seen in Figure 4.

Viewers wearing stereo glasses also experience lower brightness when this system is employed, because precious display time is devoted to emitting photons for viewers without glasses that never reach either eye of those wearing glasses. When using equal-length frames, 3D viewers experience a brightness reduction of 33%. With variable-length frames the maximum 3D brightness might increase or decrease depending on the choice of α_R.

5. EXPERIMENTS

We conducted several experiments to assess our design's viability. Subjects viewed a 42″ plasma 3DTV from a distance of approximately 1.3m; at this distance, 1 pixel subtends 0.0215 degrees.

In all 3D experiments, subjects wore 120Hz shutter glasses, and the brightness of the right eye, α_R, was progressively lowered. Subjects were instructed to respond only when they felt their eyes had adjusted, typically answering immediately for α_R near 100% and waiting about a minute for α_R near 0%. Partial adaptation to new light levels occurs immediately, with additional adaptation over approximately 20 minutes [Standing et al. 1968]. We measured only the immediate effects; significant effects have previously been found when allowing subjects to adapt to differential light levels for as little as 1 minute [Aiba and Stevens 1964] or 3 minutes [Stevens and Stevens 1963; Dodwell et al. 1968]. Ambient lighting was moderate; the Pulfrich effect has been observed under these conditions [Dodwell et al. 1968].

We measured subjects' depth perception and did not survey visual comfort. Kooi et al. tested viewer comfort with $\alpha_R = 75\%$ and found it acceptable, while Beldie et al. tested several values of α_R with two photos and found $\alpha_R = 40\%$ and 60% acceptable [Kooi and Toet 2004; Beldie and Kost 1991]. Yang et al. considered viewer comfort when each eye is shown a differerent image to achieve an HDR percept rather than depth [Yang et al. 2012].

All confidence intervals $c.i._{95\%} = \pm 2 \cdot \sigma/\sqrt{n}$ were calculated for each α_R by finding the mean m_s for each of the n subjects s and computing the standard deviation σ over the means $[m_s]$.

5.1 2D Viewer Preferences

Standard 3DTVs show a double image to 2D viewers. A 3D+2DTV removes this ghosting, but also reduces the contrast. This experiment investigates at what level of contrast viewers prefer the original, ghosted image to a lower-contrast image without ghosting.

We presented subjects with two images on a standard 2D TV, and asked them to choose which they prefer, as in Figure 5(a). On the left, we simulated the double image L+R seen on a traditional active-shutter stereoscopic display; on the right, we simulated L+R+N in accordance with the analysis of the previous section. We conducted experiments simulating simple equal-length frames (Figure 3(top)) and variable-length frames (Figure 3(middle)) with different subjects for each.

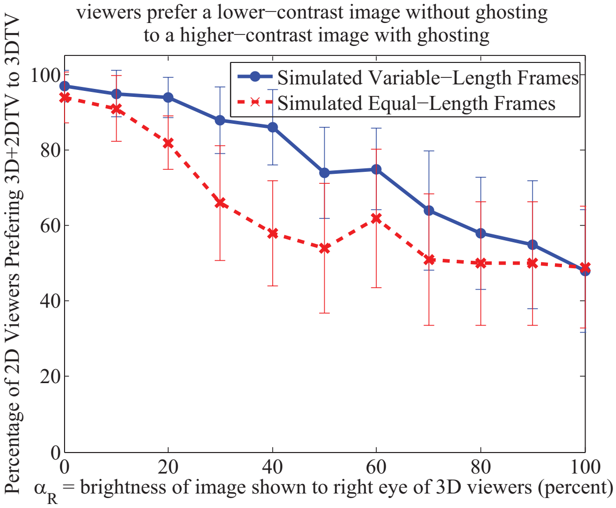
Each subject viewed ten test images at eleven values of α_R, with $n = 10$ subjects participating in each experiment.

At high contrast levels viewers nearly uniformly prefer our method. Only at very low 2:1 contrast do viewers find contrast reduction equally objectionable as ghosting (Figure 5(b)). For a display with $\alpha_R = 20\%$ and equal-length frames, 80% of our subjects prefer low-contrast images without ghosting. A display capable of producing variable-length frames is able to provide a higher contrast for the same value of α_R. With this design, the preference for our system rises to 95% at $\alpha_R = 20\%$.

5.2 3D Viewer Depth Perception

We display a brighter image to 3D viewers' left eyes than to their right eyes. However, stereoscopic vision is degraded when the

(a)



(b)

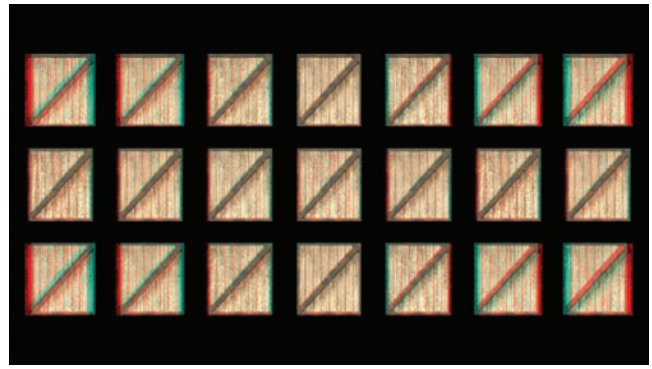
Fig. 5. (a) We showed viewers two versions of an image and asked which they prefer: (left) the ghosted double image they would see on a typical 3D display if they did not wear stereo glasses, or (right) the lower-contrast image without ghosting that they would see on our display. In this example, α_R = 30%. Thanks to Flickr user GammaMan for making this photo available under a Creative Commons license. (b) We asked subjects to choose between the image they would see without glasses on a traditional 3D TV and on our display. Note that our display is preferred by a majority of users. As the brightness of one eye decreases, the contrast ratio increases, and a greater percentage of viewers prefer our display. 95% confidence intervals shown.

images seen by each eye become disimilar [Cormack and Schor 1991]. Small brightness differences may be imperceptible, but an all-black right-eye image obviously precludes stereoscopic vision. This experiment quantifies depth perception between these extremes.

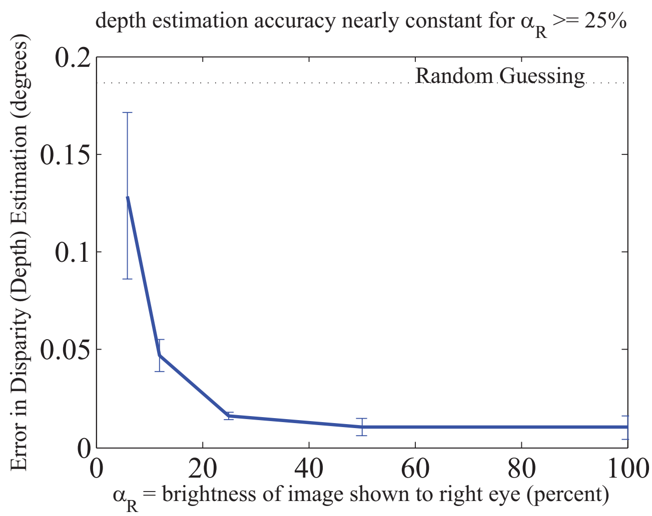
We presented subjects wearing shutter glasses with a stereoscopic display of a 7 × 3 array of wooden boxes, as in Figure 6(a). The top and bottom rows were identical and unchanged throughout the experiment, with each box in the row at a different depth, in the range of [−0.13 to +0.13] degrees disparity. The middle row of boxes were all at the same depth; this depth was varied in each trial. Subjects were asked to identify which column of the top-and-bottom-row boxes was at the same depth as the boxes in the middle row. They answered, for example, "The boxes in the middle row are at the same depth as the top and bottom boxes in column three."

> n = 6 subjects each undertook 130 trials, randomly varied across 5 different brightness levels and 13 possible depths.

We find that depth perception is surprisingly robust against differences in image brightness between the two eyes, and is not significantly affected until α_R falls below 25% (Figure 6(b)).



(a)

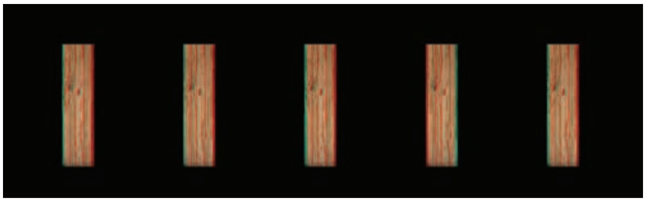


(b)

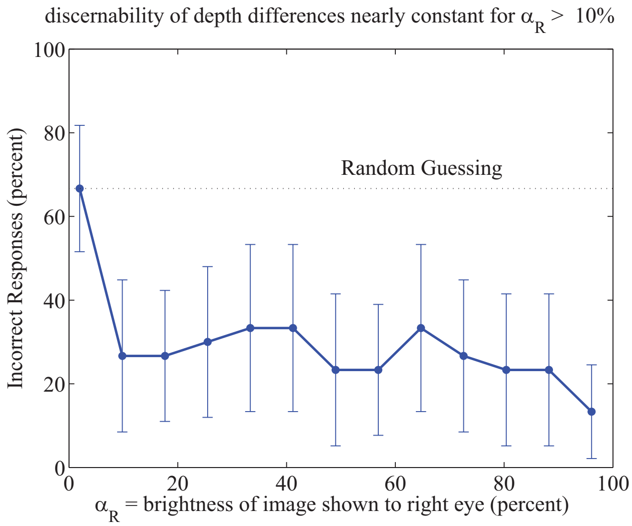
Fig. 6. (a) This experiment quantified viewers' ability to perceive depth in static images on a stereoscopic display when one eye is presented with a darker image than the other eye. The subject was shown 3 rows of boxes, reproduced here in anaglyph format for illustrative purposes. The top row and bottom row are identical, featuring 7 boxes of different disparities, with the leftmost box appearing furthest away and the rightmost box closest. The middle row contains 7 boxes, all with the same disparity. The subject was asked which column in the top and bottom rows is at the same depth as the boxes in the middle row. (b) As one eye's brightness decreases, viewers' ability to perceive depth was excellent for $\alpha_R \geq 25\%$. Here 95% confidence intervals shown.

In a second experiment, we showed subjects a set of five vertical sticks, as seen in Figure 7(a), while again the brightness of the image seen by their left and right eyes differed. One of the three central sticks was displayed with a different disparity than the other four sticks, so that it was perceived as lying at a different depth. The subject was asked to identify which stick was at a different depth than the other sticks. Each subject made judgements with α_R varied to 27 levels, binned to 14 levels in Figure 7(b). n = 15 subjects participated in the experiment. Individual trial depths were chosen randomly in the range of [0.02 to 0.15] degrees of disparity.

Viewers' ability to perceive depth differences was not impaired until the brightness of the darker eye became very dark, similarly to the previous experiment. Accuracy fell slowly from the



(a)



(b)

Fig. 7. (a) In this experiment, subjects viewed a stereo display where one eye viewed a brighter image than the other. Subjects viewed five sticks, with one displayed at a different disparity than the other four. This screen shot has been converted to anaglyph form. (b) Viewers' ability to perceive depth differences was quite good for $\alpha_R \geq 10\%$. 95% confidence intervals shown.

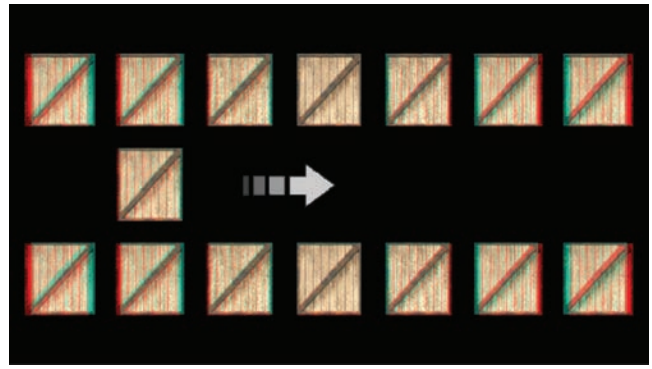
equal-brightness case until α_R fell below 10%. When $\alpha_R < 10\%$, subjects answered as if guessing randomly.

5.3 Moving 3D Objects and the Pulfrich Effect

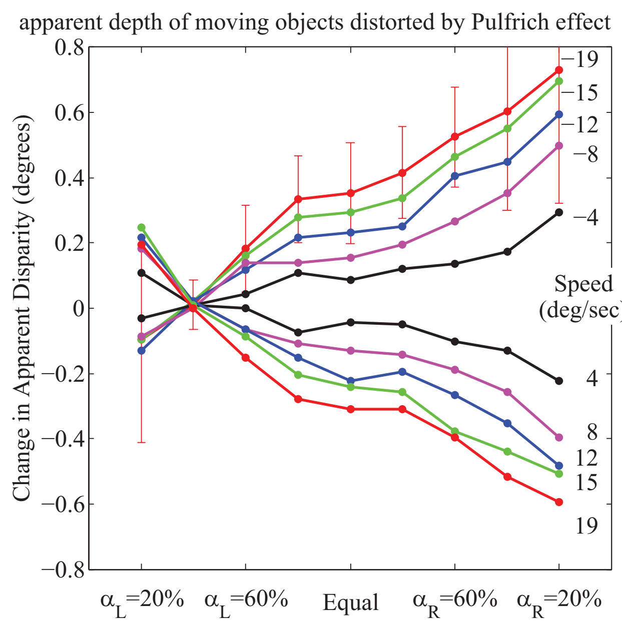
When one view of a stereoscopic image is dimmed, the Pulfrich effect produces an apparent time delay, as discussed in Section 3. In addition to the virtual time delay caused by a dimmed eye, all sequential 3D displays also experience a real-time delay: on a 120Hz display that shows (left,right) image pairs at 60Hz, the image shown to the right eye will always lag behind the image shown to the left eye (or vice versa) by 1/120th of a second (8 milliseconds). This time delay is accompanied by an attendant distortion of depth. 3D content creators often ignore this distortion: the Blu-ray 3D specification and Nvidia developer advice treat the left and right frames as simultaneous [Vetro et al. 2011; Gateau and Neuman 2010].

If the virtual time delay caused by the Pulfrich effect is of a similar magnitude as the actual time delay of sequential-frame stereo displays, we expect that it can likewise be safely ignored. We conducted an experiment to measure the impact of the Pulfrich effect on our system. We find the two effects to be of similar magnitude, and that one effect may be used to cancel out the other.

We showed subjects a 3D scene containing two rows of seven stationary boxes, as in the first experiment of Section 5.2. The boxes



(a)

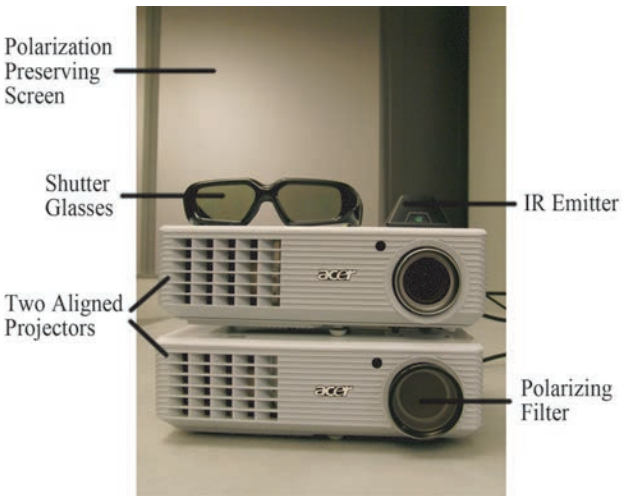


(b)

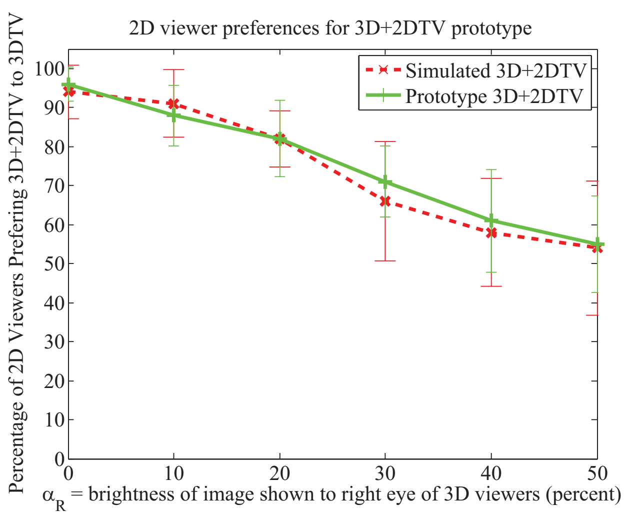
Fig. 8. (a) This experiment quantifies the impact of the Pulfrich Effect on depth perception. Subjects viewed two identical rows of seven boxes, with the leftmost boxes furthest and the rightmost boxes closest. A moving box passed between the two rows, and the subject chose which stationary box was at the same depth as the moving box. Negative speeds denote movement in the opposite direction. (b) When one eye is brighter than the other, the depth of moving objects is misperceived. Faster objects have a greater distortion in their apparent depth. A larger difference between the brightness of the two eyes also causes a greater distortion. Minimal distortion is not found at equal brightness: the sequential-stereo display's 8ms delay is cancelled at $\alpha_L = 40\%$. For clarity, 95% confidence intervals are shown for only one speed.

lie at different depths, with the leftmost pair of boxes furthest away, and the rightmost pair closest. A moving box passed horizontally between the two rows of stationary boxes, as in Figure 8(a).

The subjects were asked to identify the stationary box whose depth most closely matched the depth of the moving box. The stationary boxes were unaltered throughout the experiment, but the moving box's speed, direction, and disparity (true depth) were randomly varied. Due to the depth distortions of the Pulfrich Effect,

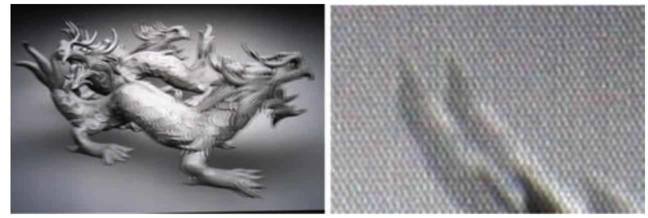


(a)



(b)

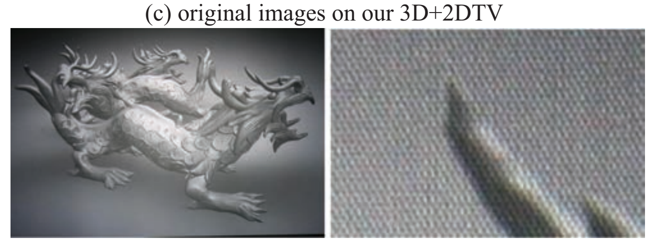
Fig. 9. (a) Our prototype uses two projectors and a polarization-preserving screen. An unpolarized 3D projector synchronized with active-shutter LCD 3D glasses shows the L and R images. A second, linearly polarized projector shows the N image. LCD shutter glasses contain a linear polarizing filter that blocks the light from the polarized projector. (b) We repeated the 2D viewer preference test with our prototype and obtained very similar results to the initial experiment. 95% confidence intervals shown.



(a) original images on a standard 3DTV

(b) Didyk et al.'s result on a standard 3DTV

(c) original images on our 3D+2DTV



(d) Didyk et al.'s result on our 3D+2DTV

Fig. 10. Here we compare our method, using a 3rd frame to cancel out one of the two stereo images, to the technique of Didyk et al., wherein the disparity between the two images is reduced. The left column shows the overall image, while the right column shows a closeup of the dragon's horns, one of the largest areas of ghosting. (a) 2D view of unmodified stereo image; (b) Didyk et al.; (c) our method with $\alpha_R = 30\%$; (d) applying Didyk et al., then our method.

the subjects estimated a consistently different depth for the moving object, depending on its speed and the brightness of each eye.

This experiment was conducted at nine levels of α (dimming either the left or right image), with the center box moving both left and right at each of five speeds. $n = 3$ subjects undertook six trials at each condition, with the center box's disparity (depth) randomly permuted (0, 0.13, or 0.26 degrees). Each data point is thus averaged over 18 responses. The illusory depths seen by the subjects are shown in Figure 8(b). Higher speeds create larger distortions, and movements in opposite directions (right/left) produce opposite depth illusions (closer/further), consistent with a time delay.

Errors are smallest when the left eye is dimmed to approximately 40% the brightness of the right eye, rather than when both eyes have equal brightness. At this value, the virtual time delay caused by the Pulfrich effect largely cancels out the 8ms delay in the sequential display of left and right stereo images. Greater brightness differentials produce larger illusions, consistent with longer latencies.

If the virtual delay were large, it would need to be offset by delaying the dimmed video feed. This appears unnecessary; the Pulfrich effect poses no obstacle to dimming one eye of a 3D+2DTV.

6. PROTOTYPE

Our protoype uses two projectors and a polarization-preserving screen, seen in Figure 9(a). A standard, unpolarized 3D (120Hz) projector synced to LCD active-shutter glasses displays the images L and R seen by the left and right eyes of the viewer wearing glasses. The second projector displays the 3rd image, N, and is

Fig. 11. Here we show several examples of our prototype in use. In each image, the projector screen is visible directly at the top of the image, and through each lens of the stereo glasses at the bottom of the image. (Left Column) A typical 3D display (Middle Column) our 3D+2D prototype, with $\alpha_R = 30\%$ (Right Column) the 3rd channel we display to cancel out the right-eye image. Thanks to Flickr users GammaMan, Trondheim_Byarkiv, and Isaiah-v for making these photos available under a Creative Commons license.

linearly polarized. The LCD glasses contain an orthogonal linear polarizer that blocks the N image from the second projector.

Note that the first projector spends half its light on the L frame and half on the R frame. The second projector spends all its light on the N frame, but half of this light is lost to the linear polarizer. This leaves all three frames with similar brightness. Geometric and photometric calibration are required to align the images and correct nonlinearities in projected brightness [Brown et al. 2005].

We evaluated our system by displaying images in standard 3D, as well as using our 3D+2D method. Figure 11 shows a number of examples at $\alpha_R = 30\%$, together with the third channel that we introduced. The example images were captured by photographing the projection screen through a pair of shutter glasses that reveals the images delivered to the left and right eyes of 3D viewers, while the region outside the glasses shows the experience of viewers without glasses. In our implementation, only very minor ghosting is visible in the 2D region, and the third channel is blocked by shutter glasses.

We repeated the 2D viewer preference test described in Section 5.1 with our prototype, testing only $\alpha_R < 50\%$, since this is the range in which our prototype and method are most useful. Viewer preferences on the prototype closely matched preferences for simulated equal-length frames on a 2D display, as seen in Figure 9(b).

We compared our prototype to Didyk et al.'s "backward-compatible stereo," which improves the 2D viewing experience by reducing stereo disparity to the minimum that still maintains a perception of depth for 3D viewers [Didyk et al. 2011, 2012]. The original stereo image is shown in Figure 10(a). The results of Didyk et al. in Figure 10(b) and our method in Figure 10(c) demonstrate that both methods greatly reduce ghosting (closeup, right), which reduces blurriness of the overall image (left). While our method completely removes ghosting, it also reduces contrast. Combining the two methods, in Figure 10(d), gives similar results to ours alone.

7. LIMITATIONS AND FUTURE WORK

Our prototype's screen exhibits significant specular reflection, limiting radiometric calibration accuracy, so that some residual ghosting remains. Its preservation of polarization is also imperfect, leaving the N image slightly visible through stereo glasses. Higher-quality components and calibration would rectify these issues.

This work focuses on completely eliminating ghosting. However, when the ghost is relatively dim, it is not as objectionable [Siegel and Nagata 2000]. Partially canceling the ghost image may prove an optimal trade-off between ghosting and contrast reduction.

Several factors affecting perceived image quality and stereo fusion and viewer comfort have been left unexplored. In-depth study may be needed before widespread deployment of such a system. Studies investigating the effects of image contrast, image content, eye dominance, and dark adaptation over time may prove insightful.

8. CONCLUSION

Many current 3D displays require that viewers wishing to see the 3D scene wear special stereo glasses; viewers without glasses not only do not see a 3D scene, but see an unappealing and confusing double image. 3D displays are often used in entertainment, engineering, and medical applications where it may be impractical or undesirable to require all viewers to wear stereo glasses.

We have demonstrated a method to produce 3D displays where viewers wearing glasses see a 3D scene, while those without glasses see a single 2D scene. We have shown that reducing the brightness of one of the images shown to the 3D viewer does not interfere with depth perception, while allowing acceptable contrast for the 2D viewer. We have also demonstrated that depth distortions due to the Pulfrich effect are only of similar magnitude to other distortions present in all sequential-stereo displays, and can offset them.

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