Analysis of the viewing zone of multi-view autostereoscopic displays

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ABSTRACT

The viewing zone of a multi-view autostereoscopic display can be shown to be completely determined by four parameters: the width of the screen, the optimal distance of the viewer from the screen, the width over which an image can be seen across the whole screen at this optimal distance (the "eye box" width), and the number of views. A multi-view display's viewing zone can thus be completely described without reference to the internal implementation of the device. These results can be used to determine what can be seen from any position in front of the display.

This paper presents a summary of the equations derived in an earlier paper. These equations allow us to analyse an autostereoscopic display, as specified by the above parameters. We build on this work by using the derived equations to analyse the configurations of the extant models of the Cambridge autostereoscopic display: 10" 8- and 16-view, 25" 28-view, 50" 15-view displays and an experimental 25" 7-view display.

Keywords: viewing zone, autostereoscopic, stereoscopic, 3D display

1. INTRODUCTION

The behaviour of an ideal multi-view autostereoscopic display is completely determined by four parameters: screen width, eye box width, number of views, and optimal viewing distance. In an earlier paper,[1] we derived the equations which describe this behaviour and compared the theoretical results with the observed behaviour of a 10", 8-view, Cambridge autostereo display. In this current paper we describe the theoretical behaviour of all of the extant Cambridge time-multiplexed displays,[2–4] and discuss their design and their actual behaviour.

2. AUTOSTEREOSCOPIC DISPLAYS

Autostereoscopic displays offer the viewer three dimensional realism lacking in conventional two-dimensional or stereoscopic displays. The combination of both stereo parallax and movement parallax produces a perceived effect similar to a white light hologram.

In real life we gain three dimensional information from a variety of cues. Two important cues are stereo parallax: seeing a different image with each eye, and movement parallax: seeing different images when we move our heads. Figure 1(a) shows an observer looking at a scene. He sees a different image of the scene with each eye and different images again whenever he moves his head. He is able to view a potentially infinite number of different images of the scene.

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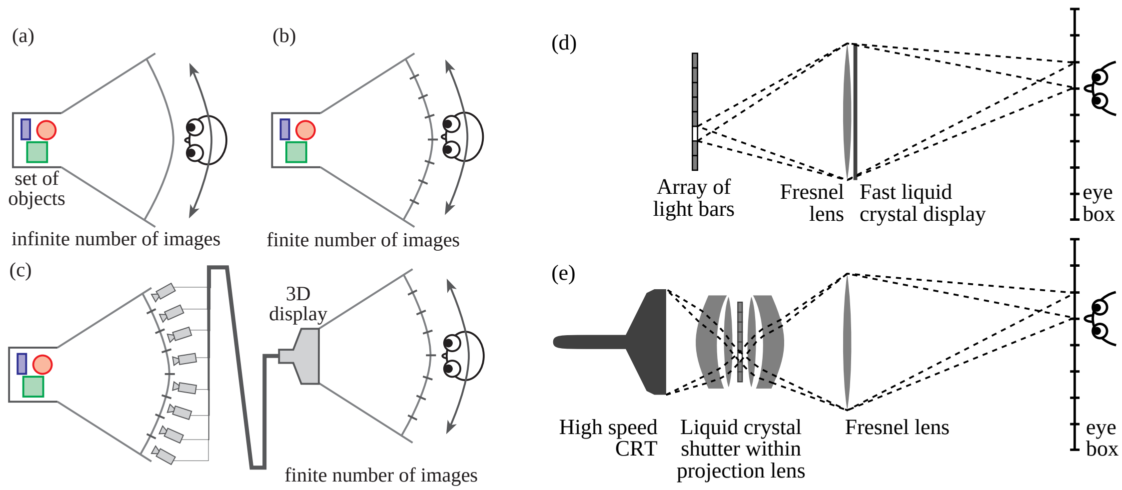

Figure 1. (a) In viewing a real world scene there are an infinite number of possible images of the scene. (b) It is possible to conceptually divide this viewing space into a finite number of windows, in each of which only a single image is visible, while still retaining both stereo and movement parallax cues. (c) An autostereoscopic 3D display uses this idea to provide a three-dimensional image using a finite number of views taken from distinct view points. (d) The conceptual design of a Cambridge autostereoscopic display. (e) The practicable design used in the 10 inch display.

Figure 1(b) shows the same viewing space divided into a finite number of *windows*. In each window only one image, or *view*, of the scene is visible. However the viewer's two eyes each see a different image, and the images change when the viewer moves his head — albeit with jumps as the viewer moves from window to window. Thus both stereo and movement parallax cues can be provided with a small number of views.

The finite number of views required in Figure 1(b) allow the replacement of the scene by a three-dimensional display that outputs a different image to each window (Figure 1(c)). This is the principle of multi-view autostereoscopic displays.

Autostereoscopic Display Technologies

A variety of autostereoscopic technologies have been developed.[5, 6] Lenticular displays and hologram displays use high resolution display devices to produce multi-view images at a lower resolution. Lenticular displays[7] use sub-pixels beneath micro-lenses. They normally provide two views, which does not provide movement parallax. Four view[8] and eight view[9] lenticular displays have been demonstrated, but precise alignment of micro-lenses and pixel array, and the high resolution required make more than four views difficult to achieve.

Hologram displays use a pixellation fine enough to form diffraction gratings. There is potential for hundreds of views to be displayed.[10, 11] However the resolution required to make a diffraction grating necessitates that the equipment be mounted on an optical bench.

Parallax barriers[7] and parallax illumination[12] provide a more flexible two-view alternative to lenticular screens, but suffer the same problems when trying to increase the number of views.

Multiple projector systems[13] avoid the resolution problem by using several projection devices imaging through an optical component such as a double lenticular lens array. While this undoubtably works, it is expensive in that one projector is required per view, and it can be difficult to precisely align the projectors for comfortable viewing.

All of these methods provide multiple views by having more spatial resolution than an equivalent two dimensional display. An alternative is to have a higher frame rate. A two dimensional display is made visible to one window at a time and the appropriate image displayed. If this process is repeated sufficiently rapidly the whole seems continuous to the human eye. There are no misalignments between the views because all

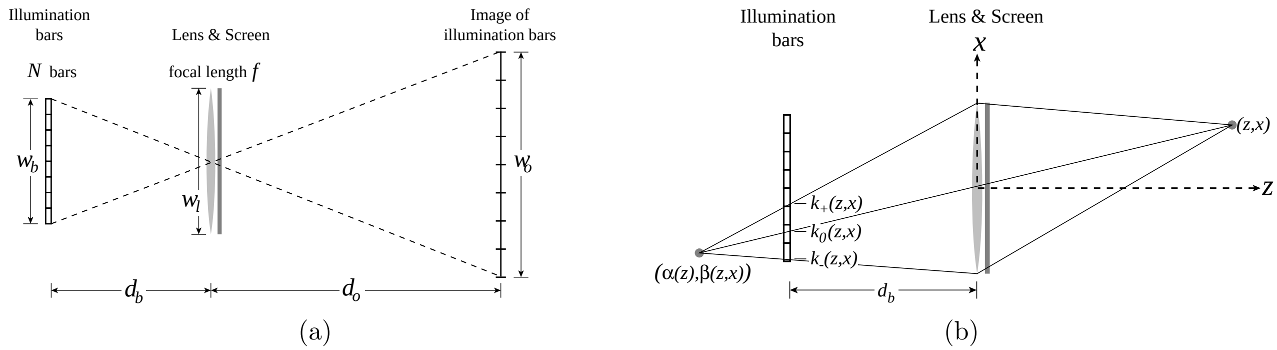

Figure 2. (a) Basic parameters of a Cambridge autostereoscopic display. (b) Image of a pupil at (z, x) is $(\alpha(z), \beta(z, x))$. At distance d_b behind the lens the point (z, x) images onto the area from $k_-(z, x)$ to $k_+(z, x)$.

of the views are displayed on the same device. This time-multiplexed method has the advantage that it is easier to increase frame rate than resolution. The Cambridge autostereoscopic displays[2–4, 14–20] use such a time-multiplexed system to achieve a laterally multiplexed autostereoscopic image.

The Cambridge Displays

The basic theoretical design of a Cambridge display (Figure 1(d)) consists of a high speed liquid crystal display, a convex lens, and a series of abutting bar shaped light sources. Each light bar is illuminated in turn. In synchronisation with this, successive laterally adjacent views of a scene are displayed on the liquid crystal display. The effect of the lens is that each view is visible from a different set of directions in front of the display. Provided that the views are repeatedly illuminated sufficiently rapidly, an observer will perceive a three-dimensional image.

Eight views displayed at a 60Hz refresh rate requires a liquid crystal display with a frame rate of 480Hz. A more desirable 32 views would require almost 2kHz. Neither speed is feasible with nematic liquid crystals, but may be attainable with smectic liquid crystals if the problem of transferring image data sufficiently quickly to the liquid crystal array can be overcome.[21]

Practicable versions of the Cambridge display have been built which utilise a CRT with a high frame rate (about 1kHz), a projection lens, and a smectic liquid crystal display element (Figure 1(e)). The CRT versions emulate the liquid crystal display and illumination system of the basic design. They are functionally identical to the ideal design.

The principle behind the display has been generally understood to be directional modulation, the optical system ensuring that each of the views is visible over only a small range of directions, as illustrated in Figure 1(d). The actual behaviour of the display is considerably more complex that this simple description, and it was analysed for the first time in a 1996 paper.[1] That analysis was the first quantitative description of the behaviour of the Cambridge display. It successfully predicted and explained the effects of the existing CRT-based displays, and proved effective in preparing designs for future models. The following section summarises the main results of that analysis.

3. SUMMARY OF RESULTS

Basic Parameters

A theoretical Cambridge display (to which the practical versions are equivalent) consists of (Figure 2(a)) a simple convex lens and adjacent display screen of width w_l, and a set of N illumination bars with overall width w_b. The bars are situated a distance d_b from the lens. The lens has a focal length f.

The system is arranged such that $d_b \geq f$. Consequently an image of the illumination bars is projected a distance d_o in front of the lens. This image has width w_o. These two parameters are related to d_b and w_b by the simple equations: $1/f = 1/d_o + 1/d_b$ and $w_b/d_b = w_o/d_o$.

An eye at d_o will see the entire screen illuminated by a point on one of the illumination bars. Each of the viewer's two eyes will be illuminated by a different bar, and hence will see a different view. This provides stereo parallax to the viewer. When the observer moves his head left-right at distance d_o, his eyes will move through zones illuminated by different bars. This provides movement parallax, allowing the observer to look around objects in the image. The combination of these two effects produces a powerful three-dimensional illusion.

Viewing at other distances still produces a three-dimensional illusion. The purpose of the analysis in the 1996 paper[1] was to ascertain what the viewer will see from *any* position in front of the screen. To achieve this it is necessary to find which parts of the illumination system illuminate the screen for all positions of the eye. This allows us to quantify the zone over which a viewer will perceive a three-dimensional effect.

The Pupil's Image on the Illumination Bars

If an eye is placed at an arbitrary point (z, x) in front of the screen (Figure 2(b)), the image of an idealised pinhole pupil will be at $(\alpha(z), \beta(z, x))$ where $\alpha(z) = fz/(f - z)$ and $\beta(z, x) = fx/(f - z)$.

The range imaged by the point (z, x) at distance d_b behind the lens covers the range from $k_-(z, x)$ to $k_+(z, x)$. These can be shown to be:

$$
\begin{aligned}
k_+(z,x) &= d_b\left(-\frac{x}{z} + \frac{w_l}{2}\left(\frac{1}{z} - \frac{1}{d_o}\right)\right), \\
k_-(z,x) &= d_b\left(-\frac{x}{z} - \frac{w_l}{2}\left(\frac{1}{z} - \frac{1}{d_o}\right)\right).
\end{aligned}
$$

These equations make no mention of the y-coordinate, which is not required in the subsequent analysis. However, the equations can be easily extended to full three-dimensional space to show that the image a distance d_b behind the lens of a point (z, x, y) in front of the lens is a rectangle bounded by k_+ and k_- in the x-coordinate and by their equivalents in the y-coordinate.

Furthermore, this range (k_- to k_+) can be mapped on to the eye box, which is a distance d_o in front of the screen. The region it maps to can be shown to be from $x = l_-$ to $x = l_+$ at $z = d_o$:

$$
\begin{aligned}
l_+(z,x) &= +\frac{w_l}{2} - \frac{d_o}{z}\left(x + \frac{w_l}{2}\right), \\
l_-(z,x) &= -\frac{w_l}{2} - \frac{d_o}{z}\left(x - \frac{w_l}{2}\right).
\end{aligned}
$$

This range is important when we extend these results to other types of autostereoscopic display. It allows us to assert that, provided we know the illumination pattern at the eye box distance, d_o, we can predict what will be seen from any position in front of the screen.

For the Cambridge displays, we can assume that the illumination pattern is simply an image of the illumination system. We can derive a function describing which parts of the screen are illuminated by which illumination bars for any position of the eye. Assume that the illumination system is divided into N equal-width bars of infinite height which abut perfectly with a sharp transitions from one bar to the next. Number the bars from 1 to N, left to right. Paramaterise the screen width into the range $p \in [0, 1]$, where $p = 0$ represents the left edge and $p = 1$ the right edge of the screen. It can then be shown that the bar, B, illuminating position p on the screen for a pupil at (z, x) is:

$$
\begin{aligned}
B(p,z,x) &= \lceil b(p,z,x) \rceil \\
b(p,z,x) &= N\left(\frac{1}{2} + \frac{d_o}{w_o}\left(-\frac{x}{z} + \left(p - \frac{1}{2}\right)w_l\left(\frac{1}{z} - \frac{1}{d_o}\right)\right)\right)
\end{aligned}
$$

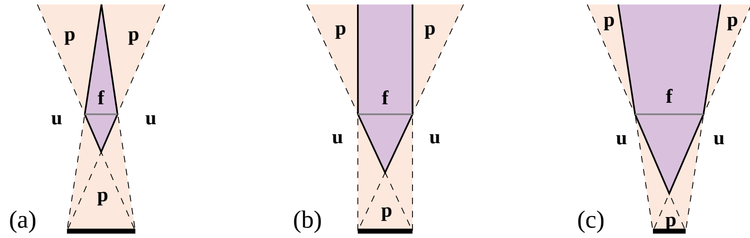

Figure 3. Three potential configurations of a Cambridge autostereoscopic display. In each the thick horizontal bar at the bottom represents the display's screen, of width w_l, while the thin horizontal line is the eye box, w_o wide at a distance d_o from the screen. (a) screen wider than eye box, (b) screen and eye box the same width, (c) eye box wider than screen. Each figure shows the umbræ (**u**), penumbræ (**p**), and fully illuminated zone (**f**).

where $\lceil a \rceil$ is the nearest integer greater than or equal to a, and $b \leq 0$ or $b > N$ is unilluminated. From this it can be seen that the behaviour of a Cambridge autostereoscopic display is completely specified by the parameters d_o, w_o, w_l, and N.

This result is important because all of these parameters are in "user space". This allows an autostereo display to be specified without reference to particular optical components, and provides the designer freedom to use whatever components are necessary to implement the design. It also allows measurement of the parameters of an existing display without the need to know the internal mechanisms of the device.

The Viewing Zones

The positions of the viewer's eye at which the entire screen appears illuminated determine the useful viewing zone of the display. Bounds on this zone can be found by setting $b(0, z, x) = 0$, $b(0, z, x) = N$, $b(1, z, x) = 0$, and $b(1, z, x) = N$. This gives the lines:

$$\begin{aligned} x &= \pm\left(\frac{z}{d_o}\frac{(w_o - w_l)}{2} + \frac{w_l}{2}\right), \\ x &= \pm\left(\frac{z}{d_o}\frac{(w_o - w_l)}{2} - \frac{w_l}{2}\right). \end{aligned}$$

These equations are equivalent to Equations (10) and (11) in the 1996 paper.[1]

Figure 3 illustrates the zones defined by these lines within which an image is visible on the screen. It will be noted that there are three distinct zones: an umbra (**u**) where nothing is visible on the screen, a penumbra (**p**) where part of the screen is illuminated, and a fully illuminated zone (**f**) where an image is visible across the entire screen. In order to see an autostereoscopic image *both* of the observer's eyes must be within the fully illuminated zone (**f**).

The front point of the fully illuminated zone (**f**) can be shown to be a distance $z_{\text{front}} = d_o w_l/(w_l + w_o)$ in front of the screen. The rear point, which only exists when $w_o < w_l$ (Figure 3(a)), is at a distance $z_{\text{back}} = d_o w_l/(w_l - w_o)$ from the screen.

For a given w_o, a larger screen size, w_l, leads to a smaller fully illuminated zone. In contrast, for a given screen size, w_l, a larger w_o leads to a larger fully illuminated zone. There are, however, limits to the size of w_o for a given number of views.

The maximum useful size of w_o is delimited by the number of views, N, and the human eye separation, s_e. This has an average value of 65 mm for adult males and 63 mm for adult females.[22] If $w_o > N \times s_e$ then there will be positions at $z = d_o$ where both eyes see the same view, and hence a monoscopic image is perceived. It is thus necessary to restrict $w_o \leq N \times s_e$. Furthermore, for a finite number of views, there will be some value of z beyond which parts of the image will appear monoscopic for the same reason. This value can be shown to be $z_{\text{max}} = d_o N s_e/w_o$. This can be considered the furthest distance at which a completely stereoscopic image

	10 inch 8-view[2]	25 inch 28-view[3]	25 inch 7-view	50 inch 15-view[4]
N	8	28	7	15
d_o	1.0 m	1.5 m	1.4 m	2.0 m
w_o	280 mm	600 mm	150 mm	330 mm
w_l	200 mm	500 mm	500 mm	1000 mm

Table 1. The parameters of the four versions of the Cambridge display. Differences in physical configuration of each display over time mean that the figures quoted here are close to but not necessarily identical to those quoted in other publications.

is visible. However, for cases where $w_o < w_l$ (Figure 3(a)) it is possible that this limiting position could be that at which both eyes can just see an image; that is: just far enough in front of z_{back} that both eyes are in zone **f**. In this case $z_{\text{max}} = \min(d_o N s_e/w_o, d_o(w_l - s_e)/(w_l - w_o))$. The limiting position close to the screen is that distance at which both eyes can first see an image across the whole screen; that is: just far enough back from z_{front} that both eyes are in the fully illuminated zone **f**: $z_{\text{min}} = d_o(w_l + s_e)/(w_l + w_o)$.

4. THE CAMBRIDGE DISPLAYS

There are four extant versions of the Cambridge time-multiplexed autostereo display: the 10 inch 8- or 16-view display[2] (Figure 10(a)), the 25 inch 28-view display[3] (Figure 10(b)), a 25 inch 7-view experimental model (Figure 10(c)) which was used in the development of the 28-view display, and the 50 inch 15-view display[4, 20] (Figure 10(d)). The 7-view experimental model was never intended for public demonstration and it exhibits a very small fully illuminated zone. It is therefore interesting to compare it against the other three variants.

Table 1 lists the important parameters for the four displays. Figure 4 shows the viewing zones of the displays to scale. Each diamond-shaped region in the figure represents an area in which the eye will see the screen illuminated by the same *set* of light bars, as illustrated in Figure 5.

Figure 6 shows what the eye sees on the screen at a variety of locations in front of the display. This shows that, at any distance other than the optimal, d_o, the image perceived by each eye can contain parts of two or more views. A second consequence is that stereo fusing of the pair of images can contain areas of differing stereo disparity. For example, in Figure 6(a) at $z = 1.2$m there are regions where the disparity between the eyes is one view and regions where it is two views.

In practice, both of these effects tend to be noticeable only when the viewer moves his or her head, provided that the view width is less than half the eye separation ($w_o/N < s_e/2$) at the optimal viewing distance (d_o), as is the case for all of the Cambridge displays. Figure 7(b) shows a photograph of the screen of the eight view display. It can be seen that the interface between views is barely noticeable, because of the similarity between adjacent views. When the head is moved, however, the fact that the image is made up of parts of several views manifests as a wiping effect: the discontinuities move across the screen. The differing stereo disparities in different parts of the picture manifest as a wobbling effect: as the disparity between the two images changes, the perceived depth of objects changes also and they can appear to wobble forwards and back. This depth wobble does not occur at or near the optimal distance (d_o), nor does it occur for objects at or near the plane of the screen (where disparity is zero).

Doubling the number of views on the 10 inch display, from eight to sixteen, is observed to significantly improve the three-dimensional illusion during head movement by reducing both of these artifacts. This is owing to the fact that each view is closer in content to its adjacent views than with eight views, reducing the wiping effect. In addition the differences in disparity in a pair of images are also reduced. The limit, as the number of views increases, is to produce a perfectly smooth three-dimensional illusion. In practice even as few as six views produces an acceptable three-dimensional effect for viewers near to the optimal distance.

A larger number of views can be used to produce a wider viewing zone (increasing w_o) or a narrower illumination region for each individual view (decreasing w_o/N). The 10 inch display has $w_o/N = 2$ for eight

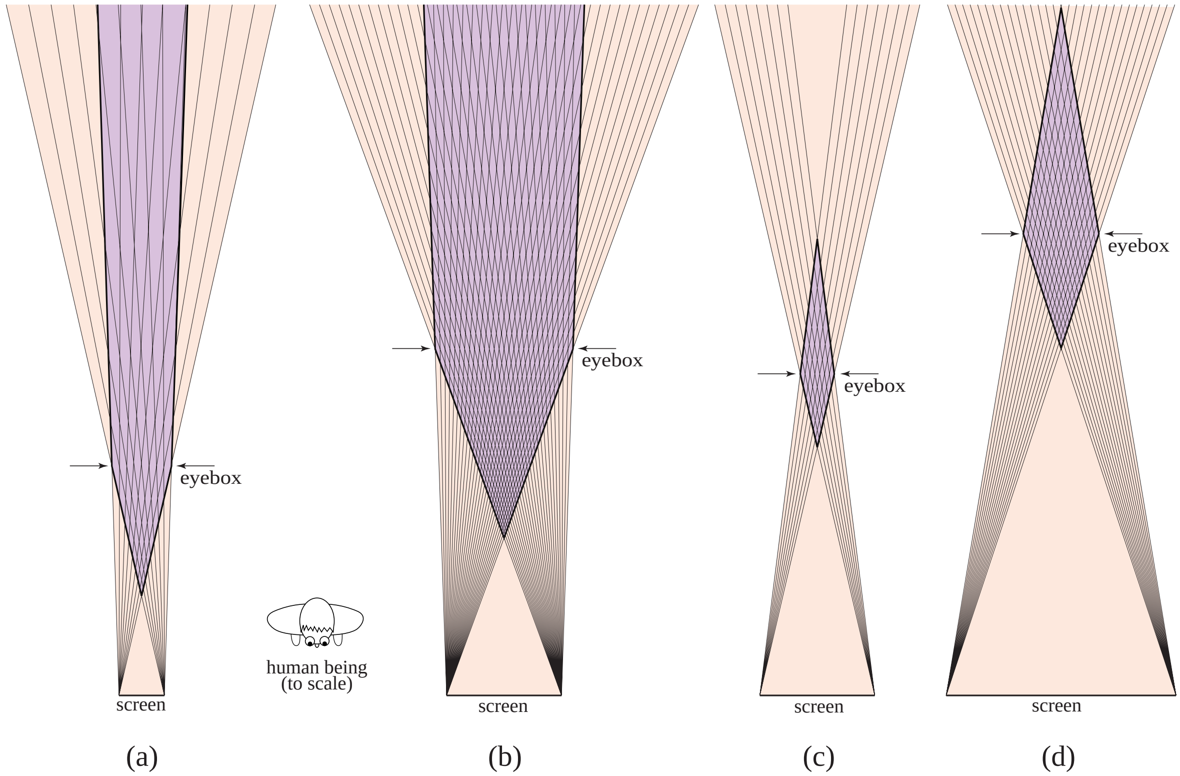

Figure 4. The viewing zones of the four variants of the Cambridge display drawn to scale: (a) 10 inch 8-view, (b) 25 inch 28-view, (c) 25 inch 7-view, (d) 50 inch 15-view. The fully illuminated region is outlined in a heavier line. Each small diamond-shaped region represents an area in which a different set of light bars illuminates the screen. The human being has an eye separation of 65 mm.

views and $w_o/N = 4$ for sixteen views. The latter has been observed, as noted above, to significantly improve the three-dimensional illusion over the eight view version. In the design of the more recent displays it was decided that $w_o/N = 3$ gives a good trade-off between stereoscopic quality and the number of views that are required.

Having chosen this number (w_o/N), we need to determine how many views are actually required. While more views are generally better, more views are more difficult to manufacture and there is a limit to the range over which a seated viewer will want to move his or her head laterally. The 15-view display was designed for a single viewer. The eye box is sufficiently wide that a single viewer is unlikely to move his or her head so far laterally that one of his or her eyes will leave the fully illuminated zone.

A second viewer would have to look over the primary viewer's shoulder to obtain a good stereoscopic image. This is also true of the 10 inch display, which is also a single viewer device. However the difference in screen size between the 10 inch and 50 inch displays leads to a differently shaped viewing zone and so, while it has been possible for the 10 inch display to accommodate up to six simultaneous viewers (the back five looking over the shoulders of those in front), the 50 inch display can realistically accommodate only two or three simultaneous viewers.

Both 10 inch and 50 inch displays are intended for a single viewer. The 25 inch display, on the other hand, was designed with a sufficiently wide viewing zone to accommodate two seated viewers side-by-side, as illustrated in Figure 8. However, the physical implementation of this display for a video game application (Figure 10(b)) has a single centrally placed seat. The viewing zone is wide enough that a number of extra viewers can cluster

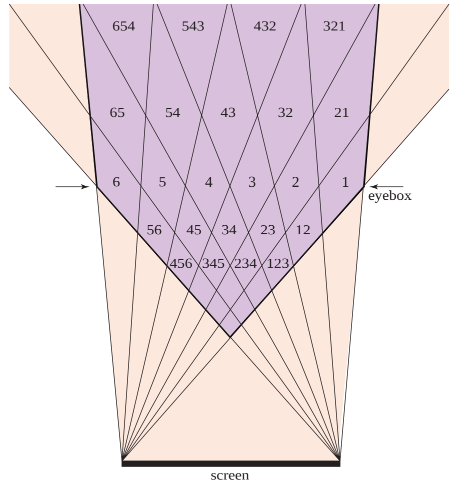

Figure 5. An example 6-view autostereo display. Some of the diamond-shaped regions contain an indication of which illumination bars illuminate some part of the screen for that entire diamond. This figure should help the reader to relate Figure 4 with Figure 6

around the seat and view the screen stereoscopically. This allows non-players to participate in the experience: an important factor in the video game market.

The 25 inch, 28-view display has an interesting internal design: it is a hybrid of time-multiplexed and multi-projector technology.[5] It consists of four subsystems, each generating seven views. Each of the subsystems behaves like the experimental 7-view display (Figure 4(c)). Abutting these four subsystems produces the much larger fully illuminated region of the 28-view display (Figure 4(b)). Unfortunately the abutting is not perfect and, as reported in an earlier paper,[3] the join is visible to the viewer. The join between the subsystems essentially means that there is a narrow darker zone on the illumination bars in three places: between bars 7 and 8, 14 and 15, and 21 and 22. These darker zones produce obvious dark bars when viewing the display from anywhere which includes one (or more) of these three boundaries. Figure 9(a) shows the resulting visual effect. Adding a low power vertical lenticular sheet on the plane of the front lens (the "screen") diffuses the dark zones sufficiently to make them unobjectionable without materially affecting the image luminance or sharpness. The result can be seen in Figure 9(b). This does not just diffuse the problematic boundaries but rather diffuses all boundaries between viewing zones. This can be seen to be a beneficial effect in that it blurs the sharp transition from one view to the next, thus reducing the wiping effect as the viewer moves his or her head. Note that it diffuses the viewing zones and *not* the image on the screen.

As mentioned above, the 28-view display is constructed from four 7-view subsystems. The experimental 25 inch, 7-view display was used as a test bed during construction of the 28-view display. It has a very small fully-illuminated region. In practice this display is only just usable by a single viewer and that person has very little freedom of movement if they wish to keep both of their eyes in the fully illuminated region. The design of the 28-view display is such that it could be populated with two, three, or four of these 7-view subsystems to make a 14-, 21-, or 28-view display. A 2-subsystem, 14-view display would be suitable for a single viewer ($w_o = 300$ mm) while a four-subsystem, 28-view display is suitable for use by two viewers working side-by-side ($w_o = 600$ mm). A three-subsystem, 21-view display is likely to be a single-viewer system and therefore will be of less utility that either the 14- or the 28-view configuration as it is more expensive than the 14-view display with little extra functionality.

5. SUMMARY

A quantitative description of the behaviour of a Cambridge autostereoscopic display has been presented. The equations presented in this paper allow for the calculation of the viewing zone of a Cambridge display, and for

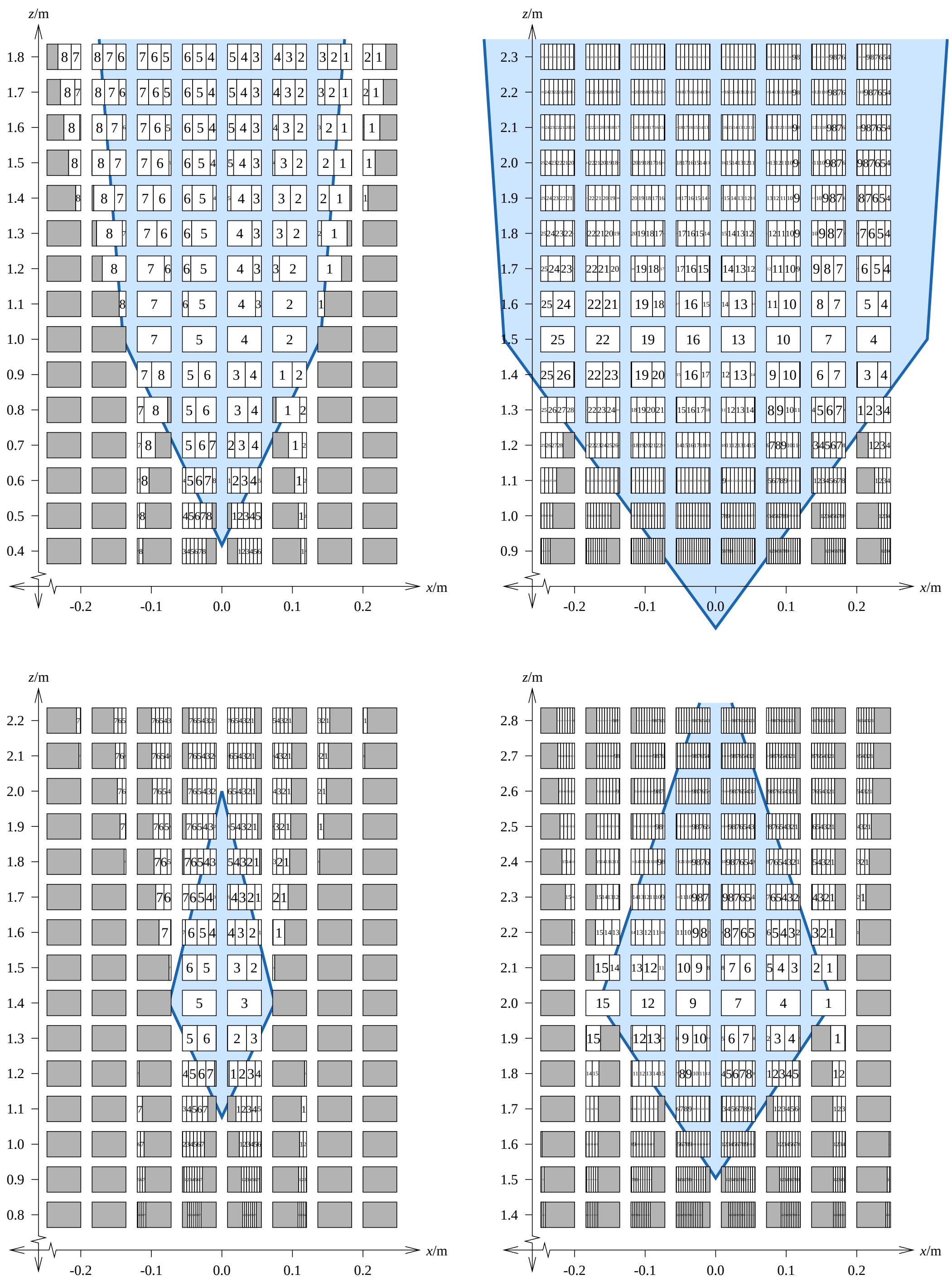

Figure 6. These figures show which illumination bars illuminate which parts of the screen at a variety of locations. The location from which each can be seen is in the centre of the rectangle. Grey indicates that that part of the screen is not illuminated by any bar, otherwise the number of the appropriate illumination bar is indicated. Horizontally adjacent screens are 64 mm (s_e) apart so that any horizontally adjacent pair represents a stereoscopic pair. Note that the x axis scale is twice that of the z axis. (top left) 10 inch 8-view, (top right) 25 inch 28-view, (bottom left) 25 inch 7-view, (bottom right) 50 inch 15-view.

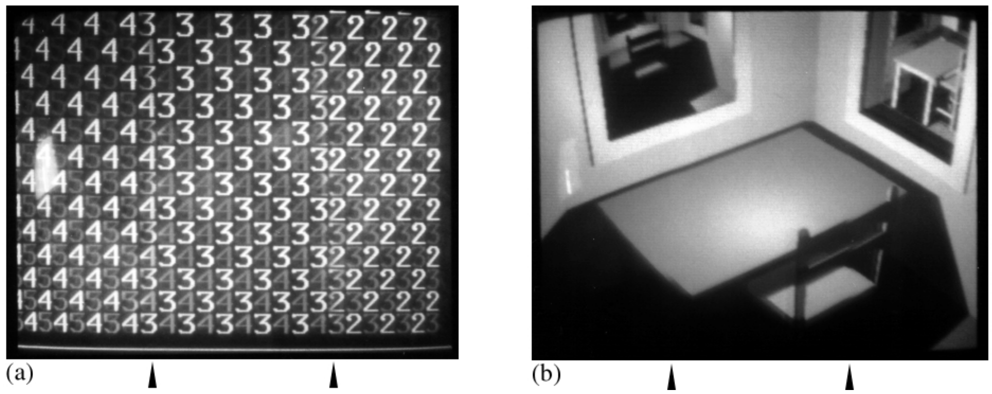

Figure 7. Photographs from the 10 inch, 8-view display's screen. (a) shows a test pattern where each view is filled with digits showing the number of that view. This clearly shows the boundaries between views. Views 4, 3, and 2 illuminate different parts of the screen from this position. (b) is taken from the same location as (a), but with a computer generated image of a room. The positions of the boundaries between the views are shown with arrows. The only noticeable artifacts of these boundaries are the slight discontinuities in the left edge of the table (above the left arrow) and in the back of the chair (above the right arrow). This demonstrates that, at least when the head is kept still, the discontinuities produce little degradation in the perceived image.

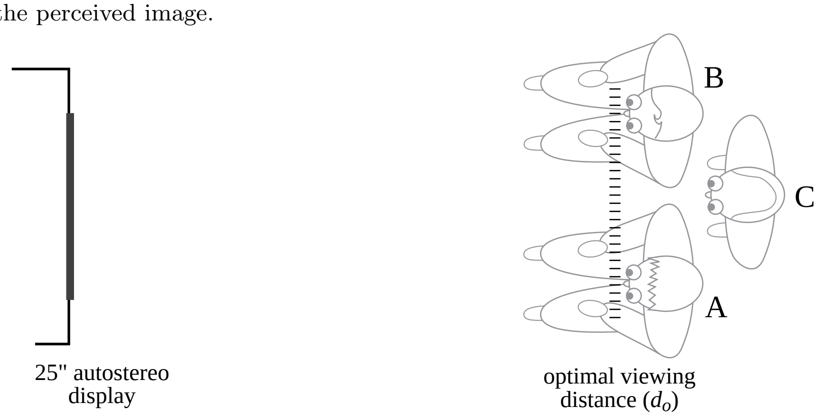

Figure 8. The 25 inch, 28-view autostereoscopic display screen, the three people, and the 28 viewing zones are drawn to scale. The optimal distance ($d_o = 1.5$ m) is also to scale. With this display, two people (A and B) can comfortably sit side by side and work collaboratively, both seeing good stereoscopic images from the correct viewpoint. Other people (e.g. C) can stand behind them and they will also see convincing stereoscopic images.

determining what a viewer will see from any position in front of the display. It has been shown that these are completely determined by by the four parameters, d_o, w_o, w_l and N (equation 9). These parameters can be used to specify the design of a Cambridge display, and suitable f, d_b, and w_b chosen to implement the design. The four extant versions of the display have been described using this methodology and features of these four versions have been discussed.

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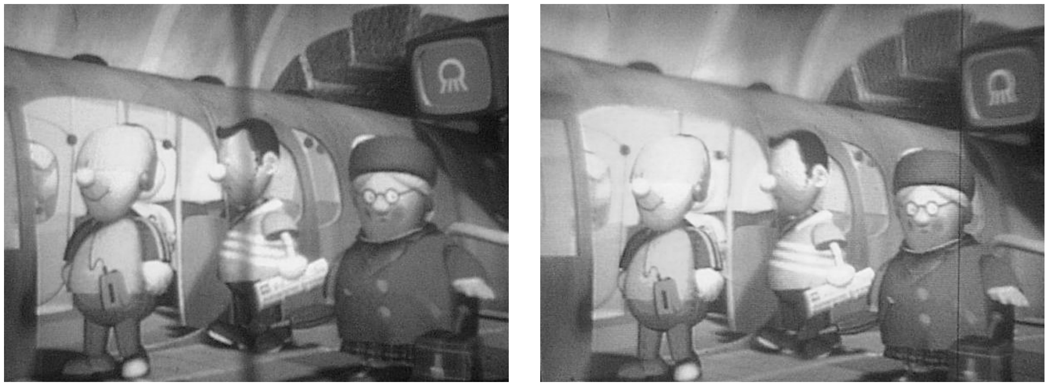

(a) (b)

Figure 9. (a) A photograph of the screen of the 25 inch, 28-view display without the diffuser. The dark line is between views 14 and 15. (b) A photograph taken from the same location after the diffuser has been inserted.

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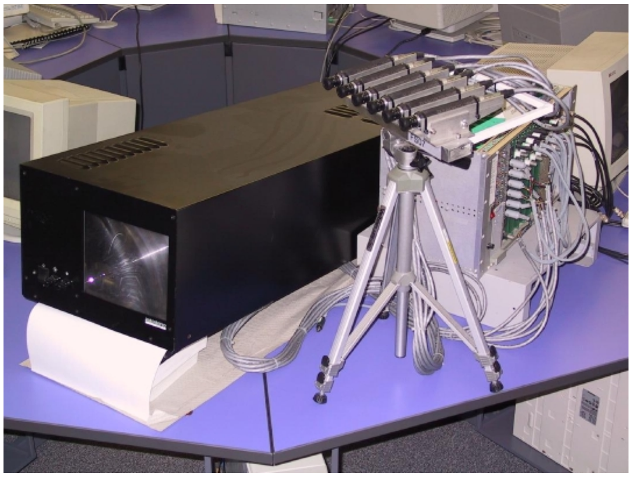
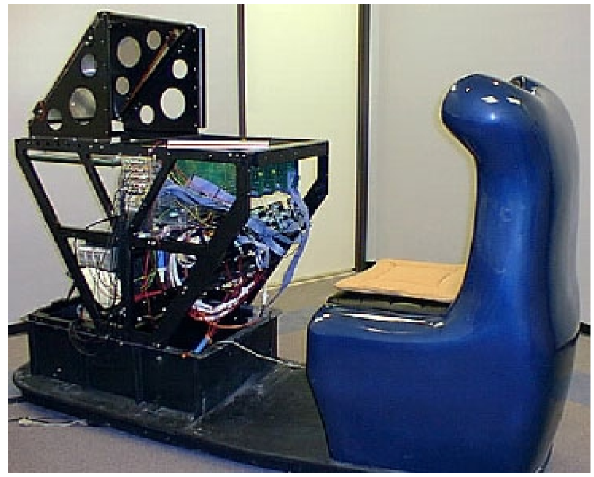
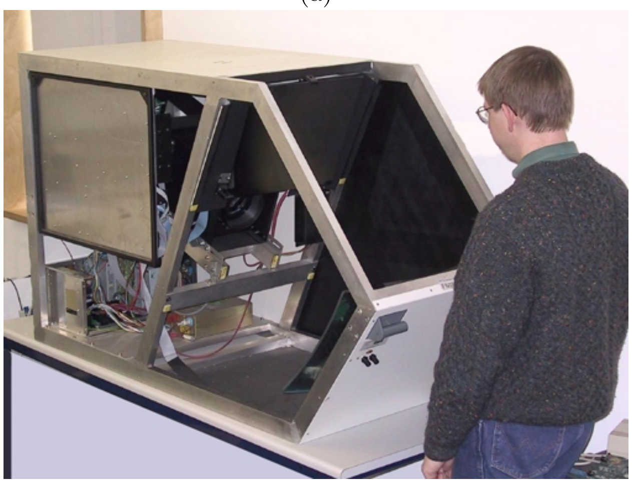


(a)



(b)



(c)

(d)

Figure 10. (a) The 10 inch, 8-view display[2] and 6-view camera system.[23] (b) The 25 inch, 28-view display.[3] (c) The experimental 25 inch, 7-view display. (d) The 50 inch, 15-view display.[4]

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