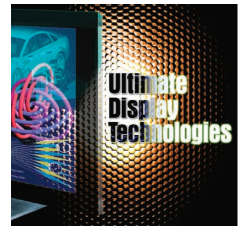
Autostereoscopic 3D Displays



Autostereoscopic displays provide 3D perception without the need for special glasses or other headgear. Drawing upon three basic technologies, developers can make two different types of autostereoscopic displays: a two-view, head-tracked display for single-viewer systems or a multiview display that supports multiple viewers.

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Most of the perceptual cues that humans use to visualize the world's 3D structure are available in 2D projections. This is why we can make sense of photographs and images on a television screen, at the cinema, or on a computer monitor. Such cues include occlusion (one object partially covering another), perspective (point of view), familiar size (we know the real-world sizes of many objects), and atmospheric haze (objects further away look more washed out).

Four cues are missing from 2D media:

- *stereo parallax*—seeing a different image with each eye,
- *movement parallax*—seeing different images when we move our heads,
- *accommodation*—the eyes' lenses focus on the object of interest, and
- *convergence*—both eyes converge on the object of interest.

All 3D display technologies (*stereoscopic* displays) provide at least stereo parallax. *Autostereoscopic* displays provide the 3D image without the viewer needing to wear any special viewing gear.[1]

3D WITH GLASSES OR HEADSETS

The well-known 3D displays that require the viewer to wear special glasses present two different images in the same display plane. The glasses select which of the two images is visible to each of the viewer's eyes. Technologies for this include

- a standard color display combined with colored glasses (the *anaglyph* method);
- two standard displays, made coplanar by a half-silvered mirror, combined with polarized glasses;
- two projectors, projecting onto a polarity-preserving screen, combined with polarized glasses; and
- a double-frame rate display combined with shuttered glasses.

All of these displays have had limited commercial use.

Early stereoscopic cinema employed *anaglyphs*—in which the right component of a composite image, usually red in color, is superposed on the left component in a contrasting color to produce a 3D effect when the viewer looks through correspondingly colored filters worn as glasses—but the prolonged use of this technology is widely reported to cause headaches.[2] Shutter glasses, notably those produced by Stereographics, are used for scientific applications.

Polaroid glasses are becoming the norm for stereoscopic cinema, but the equipment and expertise required to operate stereoscopic cinema correctly make it more costly than conventional monoscopic cinema. About half the world's IMAX cinemas can now project stereoscopic movies with the viewers using either Polaroid or shutter glasses.

An alternative to glasses is to mount two small displays in a headset—one display for each eye. Today's technology makes such devices lightweight. These devices have a range of applications but are

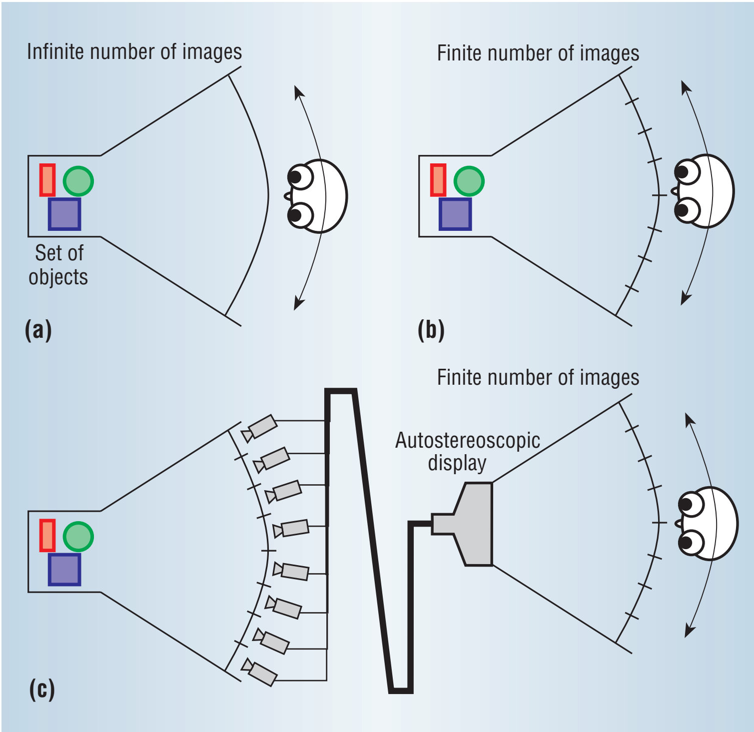
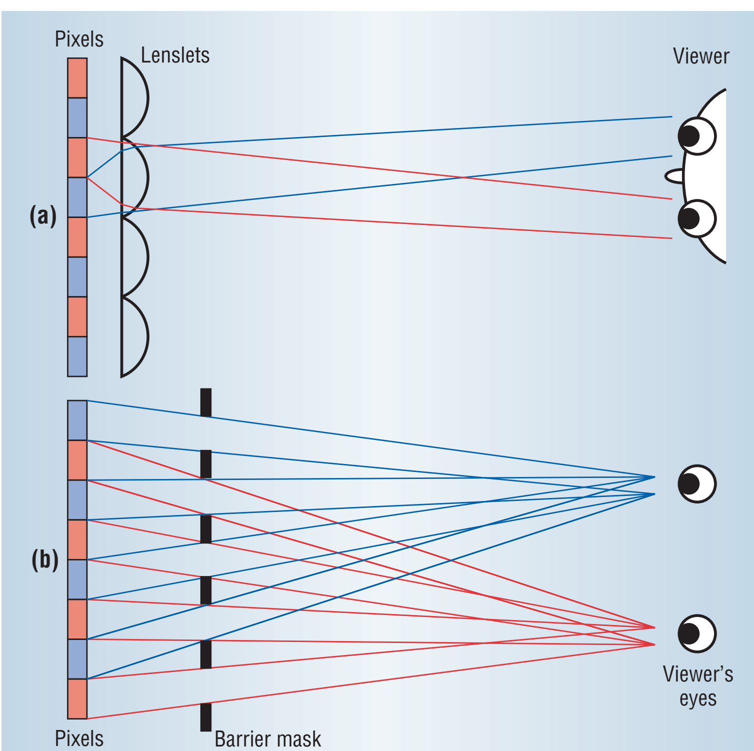


Figure 1. Multiview stereoscopic display principle. (a) Stereo parallax: When viewing a scene in real life, an observer sees a different image with each eye. Movement parallax: When he moves his head, the viewer sees different images. The viewer could see an infinite number of different images of the scene. (b) The number of images is finite, each visible in its own slot. Stereo parallax: Each eye still sees a different image; movement parallax: each eye sees different images when the viewer moves his head. (c) An autostereoscopic 3D display provides a different image to each slot, producing both stereo and movement parallax with a small number of views.



limited by the need to wear the headset and the isolation from the real world caused by being able to see only the head-mounted display. See-through headsets are available, but the display is then always seen against the background of the real world, again limiting their applicability.

All these technologies provide stereo parallax and convergence cues. When combined with head-tracking, they can provide movement parallax for a single viewer.

AUTOSTEREOSCOPIC DISPLAY PRINCIPLES

Multiview and head-tracked autostereoscopic displays combine the effects of both stereo parallax and movement parallax to give 3D without glasses. The best implementations produce a perceived effect similar to a white-light hologram.

Figure 1 illustrates the multiview autostereoscopic display principle. In Figure 1a, when an observer looks at a scene in the real world, he sees a different image with each eye and different images again when he moves his head. The observer can view a potentially infinite number of different images of the scene.

Figure 1b shows the same viewing space divided into a finite number of horizontal slots. In each slot 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 slot to slot. Thus, a small number of views can provide both stereo and horizontal movement parallax cues.

The finite number of views required in Figure 1b allows replacing the scene with a 3D display that outputs a different image to each slot, as Figure 1c shows.

Head-tracked displays, in contrast, display only two views to appropriate slots, tracking the viewer's head so that each eye always sees the correct view. If the image-generation process takes the head position into account, it can simulate movement parallax effects. Otherwise, a head-tracked display only provides stereo parallax.

Figure 2. Two ways of manufacturing a two-view spatially multiplexed autostereoscopic display. (a) Lenticular: An array of cylindrical lenslets is placed in front of the pixel raster, directing the light from adjacent pixel columns to different viewing slots at the ideal viewing distance so that each of the viewer's eyes sees light from only every second pixel column. (b) Parallax barrier: A barrier mask is placed in front of the pixel raster so that each eye sees light from only every second pixel column.

All autostereoscopic displays use optical components to achieve the effect of having different images visible on the same plane from different points of view.

AUTOSTEREOSCOPIC DISPLAY TYPES

There are three rather arbitrarily categorized types of autostereoscopic displays:

- two-view displays;
- head-tracked displays, normally two-view; and
- multiview displays, with three or more views.

The first type of display provides a basis for understanding the other two.

Two-view displays

Researchers have been using either parallax barrier or lenticular sheet technology to make two-view autostereoscopic displays for more than a century.[1,3,4]

As Figure 2 shows, two-view spatially multiplexed autostereoscopic displays can be manufactured in two ways. These displays divide the horizontal resolution of the underlying, typically liquid crystal, display device into two sets. One of the two visible images consists of every second column of pixels; the second image consists of the other columns. The two images are captured or generated so that one is appropriate for each of the viewer's eyes.

As Figure 3 shows, the two displayed images are visible in multiple zones in space. When standing at the ideal distance and in the correct position, the viewer will perceive a stereoscopic image.[5] However, there are numerous practical problems: There is a 50 percent chance the viewer will be in the wrong position and see an incorrect, pseudoscopic image; the viewer must stay fairly still to remain in the correct viewing position; and moving much forward of or back from the ideal distance greatly reduces the chance of seeing a correct image.

These limitations necessitate using another autostereoscopic solution: either introducing head-tracking or increasing the number of views.

Head-tracked displays

As Figure 4 shows, if a two-view head-tracked display knows the position of the viewer's head, it can display the right and left images in the appropriate zones, thus preventing pseudoscopic viewing. However, problems occur when the viewer's eye separation differs significantly from what the display expects.

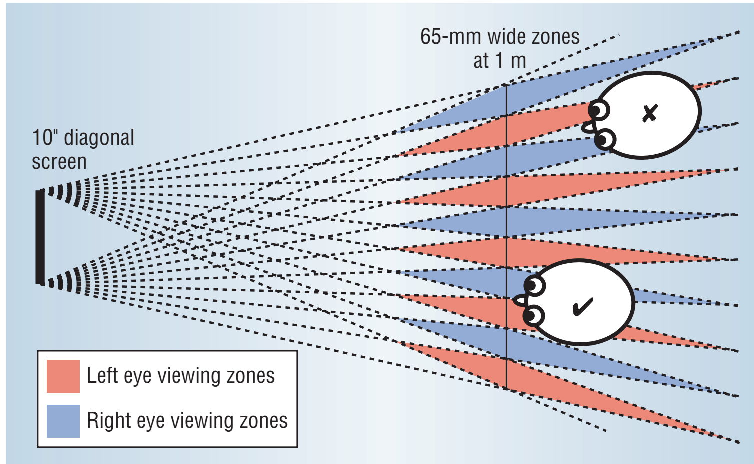


Figure 3. A two-view parallax barrier or lenticular display produces multiple viewing zones. An eye in one of these zones will see either the left or right image. An eye outside the shown zones will see an image made up of parts of both the left and right images. Even at the ideal viewing distance, there is a 50 percent chance that the viewer will see an incorrect, pseudoscopic image.

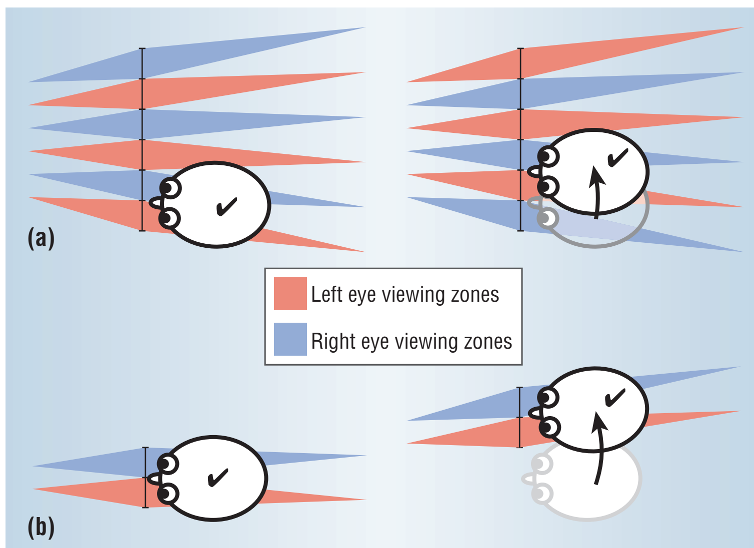


Figure 4. Two-view head-tracked displays. (a) With head-tracking, the zones can be swapped over as the viewer moves his or her head. This obviously only works for a single viewer at a time. (b) An alternative mechanism for head-tracking produces only two zones, but the display device can control where those two views are in space.

Alternatively, as Figure 5 shows, entirely different technology can display only two zones and allow them to be physically moved. The display in Figure 5a, developed by Xenotech,[6] can implement two different tracking methods: Either the projectors are moved to move the viewing zones or the entire display rotates to follow movement of the viewer's head. In the display in Figure 5b, which is similar to the technology developed by Sharp Electronics,[7] the light source must be moved to move the viewing zones.

The difficulties with head-tracked autostereoscopic displays occur in the tracking. Head-tracking should

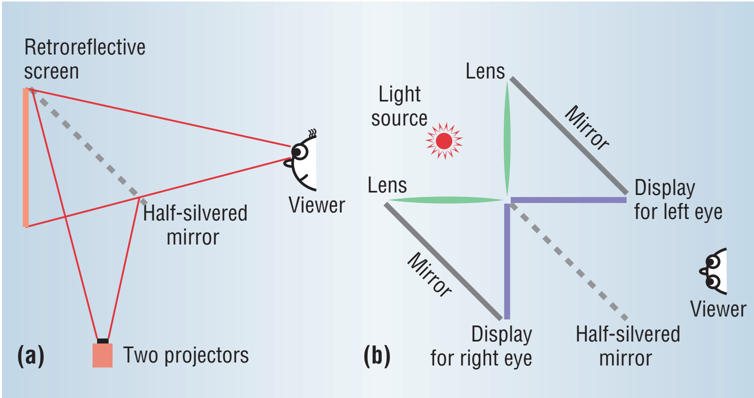


Figure 5. Two-view two-projector displays. (a) The two projectors use a half-silvered mirror to project the image onto a retroreflective screen. This screen reflects light back in exactly the direction from which it arrived. The light passes through the mirror and makes two viewing regions in space, one matching the location of each projector's lens. (b) One light source illuminates two transparent displays, which are combined with a half-silvered mirror. When the two normal mirrors are slightly offset, they cast an image of the light source to two separate viewing zones, one for each eye, so that each eye sees just one of the two displays.

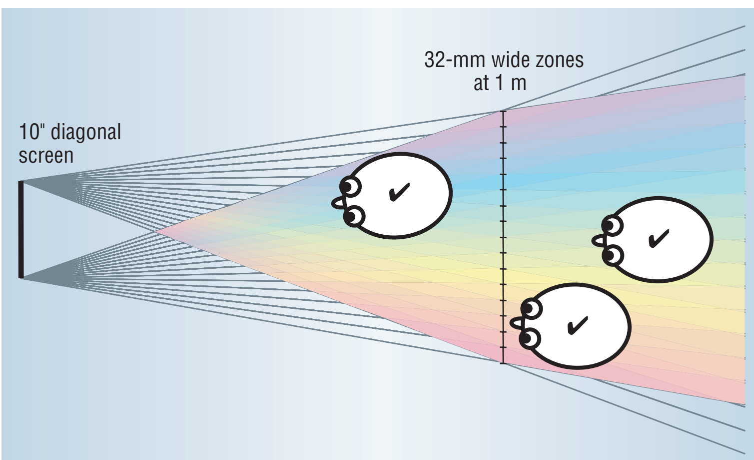


Figure 6. A 16-view autostereo display. When both of their eyes are in the viewing zone, the viewers see a 3D image.

not require the user to wear any special equipment: It would be pointless to replace wearing special glasses with wearing a special head-tracker. Head-tracking technology is now sufficiently robust that this is not a major problem, but the system must be designed to have minimal lag so that the user does not notice the head tracking.

The second problem is in physically moving the zones. The examples in Figure 5 use mechanical movement, which must be both rapid and robust. Other methods do not require mechanical movement, such as using a liquid crystal display to form the parallax barriers.

Another limitation of most head-tracked systems is that they are single-viewer. This is acceptable in some applications, but other applications require a multiview alternative.

Multiview displays

As Figure 6 shows, the advantage of multiview displays is that viewers perceive a 3D image when both of their eyes are anywhere within the viewing zone. This type of display accommodates multiple viewers, each seeing 3D from his or her own point of view.[5] Looking around objects in the scene simply requires moving the viewer's head. Head-tracking, with its associated complexity and lag problem, is not required.

The disadvantages of multiview displays include the difficulty of building a display with many views and the problem of generating all the views simultaneously because each view is always being displayed, whether anyone can see that particular view or not.

AUTOSTEREOSCOPIC DISPLAY TECHNOLOGIES

Developers use three broad classes of technology to make autostereoscopic displays:

- *spatial multiplex*—the resolution of a display device is split between the multiple views;
- *multiprojector*—a single projection display is used for each view; and
- *time-sequential*—a single very fast display device is used for all views.

Each of these three options has advantages and disadvantages.

Spatial multiplex

Past efforts have used parallax barriers, parallax illumination, and lenticular sheets[3,4] to divide a display device's resolution between two or more views. The display must have a fixed pixel pitch to allow aligning the barrier or lenslets with the pixel structure. Constructing a CRT with sufficiently precise pixel pitch is extremely difficult, and this limitation effectively requires using either liquid crystal or plasma devices for multiplexed displays.

The constraints on pixel size and resolution in liquid crystal and plasma displays limit traditional horizontal multiplexing to four views, which is barely sufficient for a multiview display. In addition, parallax barriers cause considerable light loss for more than two views, and the barrier structure becomes increasingly apparent as the number of views increases.

Lenticular displays disturbingly magnify the underlying device's subpixel structure, causing dark zones between viewing slots. Cees van Berkel and John Clarke demonstrated a seven-view display using a liquid crystal panel and a lenticular sheet on a slight diagonal.[8] Their design uses both horizontal and vertical multiplexing to provide a 3D display with reasonable resolution in both dimensions that ameliorates the dark-zone problem. Stereographics has produced a range of nine-view displays using this technology. Opticality Corporation (formerly X3D) has developed an alternative that uses holographic optical elements as the light-directing mechanism, including a 180-inch demonstration display.[9]

Making a lenticular display with spherical rather than cylindrical lenslets creates a device with full parallax (parallax in both dimensions), referred to as integral or Lippmann imaging. This type of imaging requires extremely high resolution in the underlying display device because each lenslet must have an entire image underneath it, and no commercially practical active display has yet been produced.

Multiprojector

Two-view two-projector displays can be made in several ways. While expanding the method shown in Figure 5a beyond two views by adding more projectors is straightforward, it is not easily possible to extend the method shown in Figure 5b to more views.

Figure 7 shows another method for creating multiview multiprojector displays by using a single projector for each view and projecting the images onto a special transmissive or reflective screen, such as a double lenticular sheet.

Using either of these methods, such displays are expensive: The cost of having one projector per view becomes exorbitant for even a reasonable number of views. These displays also require that the projected images must be aligned precisely with one another.

Despite these problems, experimental systems have been produced with more than 100 views.

Time-sequential

Time-sequential displays use a single display device running at a high frame rate. A secondary optical component is required to direct the images to the appropriate zones in space.

Figure 8a shows a theoretical time-sequential implementation in which turning on one of the illumination bars would illuminate the screen through the lens, and the lens would direct the light to one of the viewing zones. An eye in the illuminated zone would see the image on the screen; eyes elsewhere would see a black screen. Rapidly changing the image on the screen in synchronization with changing which illumination bar is turned on produces a multiview autostereoscopic display.

Because no technology currently exists to create this theoretical implementation, the Cambridge team developed a practical implementation, shown in Figure 8b, that retains the front lens but projects the image onto the lens from a high-speed CRT.[10,11] Ferroelectric liquid crystal shutters in the heart of the projection lens direct the light to the different viewing zones.

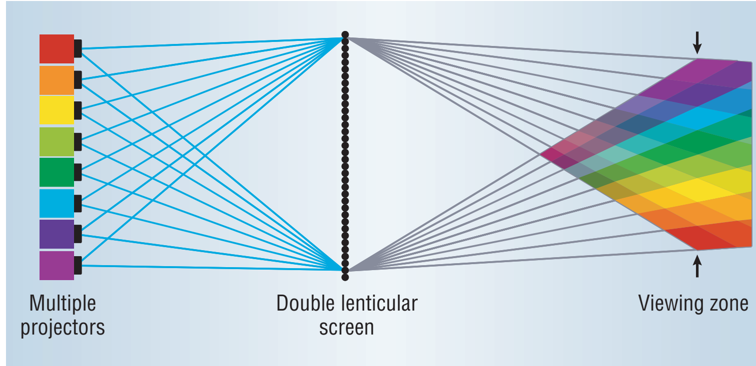


Figure 7. Multiprojector display. The image from each projector is visible across the entire double lenticular screen, but only from within the corresponding region at the optimal viewing distance (arrows). Viewing from elsewhere inside the viewing zone (the entire colored region), either forward or back from the ideal distance, also provides a 3D image.

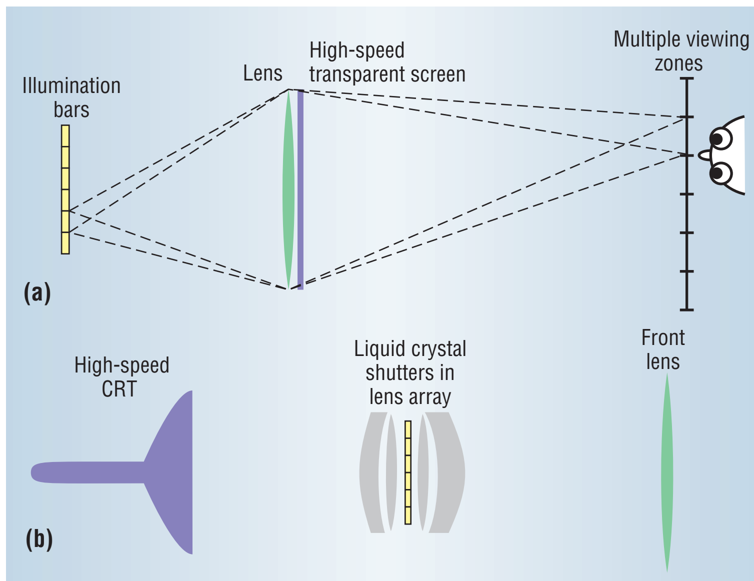


Figure 8. Time-multiplexed display. (a) Theoretical implementation: Turning on one of the illumination bars illuminates the screen through the lens, and the lens directs the light to one of the viewing zones. An eye in the illuminated zone sees the image on the screen; eyes elsewhere see a black screen. Rapidly changing the image on the screen in synchronization with changing which illumination bar is turned on produces a multiview autostereoscopic display. (b) Practical implementation: The front lens is retained, but the image is projected onto the lens from a high-speed CRT. Ferroelectric liquid crystal shutters in the heart of the projection lens direct the light to the different viewing zones. Colors indicate the correspondence between the theoretical and practical implementations.

Hybrid systems

Combining two of these mechanisms can produce a system with a higher number of views more cost-effectively. Developers have combined spatial multiplexing and multiprojector displays to produce prototypes with numerous views—for example, 40-view and 72-view experimental displays were both reported in the mid 1990s.[12,13] Combining time-sequential and multiprojector methods has led to 28-view 25-inch[10] and 15-view 50-inch[11] versions of the Cambridge display, and DeepLight is undertaking further development.

COMMERCIAL CONSIDERATIONS

Manufacturers have been producing glasses-based stereoscopic display systems for decades, and usable glasses-free autostereoscopic systems have been available for a few years. These systems have found practical uses in applications in which 3D depth perception is vital and where the novelty of stereo parallax is a selling point. The former category includes scientific and medical visualization of complex 3D structures and remote manipulation of robots in dangerous environments. The latter includes computer games and advertising.

Beyond these niche applications it is unclear whether autostereoscopic displays will have other future markets. Because these displays offer extra perceptual cues that are useful to a range of at most a few meters, they offer no added value for some applications such as flight simulators. In addition, humans are very good at interpreting 2D projections, so there are many other applications where stereo parallax is irrelevant.

When we reach the point where an autostereoscopic display becomes available that offers the same quality as a conventional display for about the same price, autostereoscopic displays might break out of their niche markets. However, it is unclear whether 3D display will ever become the norm, taking over from 2D in the way that talking pictures replaced silent movies and color replaced black-and-white movies and television. ■

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