Visual Perception and Holographic Displays

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Abstract
Holographic displays have the potential to reproduce the natural parallax and focusing affordances of real scenes. Although holographic displays are still far from maturity, no other display technologies have the potential to reproduce these affordances as accurately. This paper outlines current methods for generating images using electronic holography, and reviews visual human-factors considerations for current and future holographic displays.

1. Introduction
Holograms can produce highly detailed images that can have an uncanny visual realism. Image appearance can change instantly and naturally with the viewer's head motion, allowing viewers to experience direction-sensitive effects, like a shifting reflection on a glossy surface, or the discovery of objects hidden behind others. In addition, viewers can selectively focus their eyes on different parts of the image, allowing natural exploration of both near and far subjects, and producing natural defocus for other objects in the scene. Despite this potential, holographic display systems are still in their infancy. Analog holograms that fully produce the effects above have extremely high information content, requiring digital displays to move orders of magnitude more data than traditional 2D displays in order to achieve the same visual fidelity. Current holographic displays make computation and transmission practical by reducing information content in places that have the lowest perceptual impact. Some of these techniques are adapted from traditional display holography, while others were developed solely for digital holograms. This paper reviews the capabilities of the human visual system that are of interest to designers of holographic display systems, highlighting the differences of holographic displays from other, more widely available display technologies. Although very little vision research has been conducted with holographic images, work in related areas is can also provide insight into constraints on the perception of holograms.

2. Holography
For the purposes of this paper, we define, holography as the re-creation of appearance of a visual scene by exploiting diffraction to reconstruct light wavefronts. Wavefronts reconstructed by holography are then available to be viewed and focused by the eyes of an observer, in the same way a viewer can interact with the light emanating from a natural scene.

2.1. Computer-generated holography
The first holograms used interference of light to capture a representation of the wavelength-scale pattern of the amplitude and phase (often called "fringe pattern") of light striking a photographic plate. Computer-generated holography uses a simulation of this process to compute such fringe patterns from digital representations of scenes. These computed fringe patterns can be printed optically in photosensitive materials for viewing, or can be reproduced electronically (electro-holography) by re-creating the fringes in an electronically updatable light modulator. Electro-holography requires light modulators that control the amplitude and/or phase of light at a scale small enough to produce diffraction. Devices commonly used include liquid-crystal and MEMS light modulators, and acousto-optic devices.

2.2. Displaying Holograms
To reconstruct wavefronts from a hologram (either traditional photographically captured or computer-graphics holograms), the material containing fringe patterns is illuminated with some light source. Light that is modulated by the fringes contains the wavefronts that can then be viewed by an observer. Depending on the type of light modulator used, light illuminating the hologram may be passed through or reflected back from the fringe pattern, and may be viewed directly, or through some (for example magnifying) optical system.

The type of illumination required depends on the properties and geometry of the light modulator used to display the holographic fringe pattern. Although only a two-dimensional fringe pattern is needed to reconstruct a hologram, these "thin" holograms contain no color information. Since the angle of diffraction by fringes is wavelength-dependent, thin holograms produce differently scaled images for each wavelength of illuminating light. These holograms appear most clear when illuminated by monochromatic or nearly monochromatic light.

Holographic fringes can also be recorded in the volume of the light modulating material. In such a "thick" hologram, illuminating light along a straight path can encounter many reflecting surfaces, which can produce wavelength-selecting Bragg reflections. Thick holograms that can produce Bragg-reflections can contain color information, and can be illuminated under white light. Although electronically controlled volumetric (thick) light modulators can in principle be developed, most work on electro-holographic displays uses light modulators that control the properties of a medium over only one or two dimensions.

2.3. Spatial frequency and view zone
Holograms require modulation of light on a scale much smaller than is needed with conventional displays. In general, an electro-holographic display that can correctly illuminate a view-zone with light of wavelength λ over a viewing angle θ requires a diffraction pattern with a maximum spatial frequency of $\sin(\theta)/\lambda$. For green light, a display that can be viewed over a range of 30 degrees requires fringes spaced about one micron apart, and thus pixels spaced a half-micron apart. For a meter-wide display, each row of the display would require two million pixels. This is about one thousand times the horizontal resolution of current High-Definition TV.

Holographic displays that most completely reproduce natural scene appearance require a light modulator with similarly high resolution in both horizontal and vertical directions, and thus a square meter-sized display with a 30-degree horizontal and vertical view zone would have a pixel count on the order of 10^{12} pixels. Current prototype displays larger than a few centimeters generally create holograms by tiling or otherwise multiplexing smaller light modulators. [1] Some holographic displays reduce the information requirements by creating images that are

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holographic only in the horizontal direction. These Horizontal-parallax-only (HPO) displays contain one-dimensional holographic fringes on each display row, but have vertical resolution of only a few hundred or thousand lines. Taking advantage of the horizontal separation of viewer's eyes, these holograms can display correct (or nearly correct) images to both eyes simultaneously. HPO holograms can also maintain correct parallax under horizontal head motion. In exchange for this savings in information content, HPO displays sacrifice both vertical motion parallax (see section 3.1.2) and vertical defocus blur (section 3.1.3).

One notable approach to lowering the information requirements for driving electro-holographic displays is to dramatically reduce the view zone to less than a degree (covering little more than the viewer's eye). Such a display can use a light modulator of much lower density, but shows images that are only visible from a highly constrained portion of the space in front of the display. To compensate for all but trivial viewer head movement, displays of this kind have been designed that track the viewer's eye locations, and steer the output of the display to follow a viewer's two eyes [2].

3. Visual Perception

This section reviews vision research relating to specific aspects of visual perception that come into play when viewing holographic and related 3D displays.

3.1. Depth Perception

Human viewers estimate their distance from objects by combining information from visual and other sources. Sources of visual information that can reveal distance or relative distance are referred to as "depth cues."

3.1.1. Pictorial information

Pictorial cues are aspects of a scene that allow a viewer to discern depth using only information that appears on the retina of a single, nonmoving eye. Pictorial cues are those used when we discern thee-dimensional form depicted in two-dimensional photographs or illustrations. These cues include geometric cues, like the relative size and position of objects, blur gradients indicating deviations of objects from the plane of focus, color shifts due to atmospheric effects, and others [3]. Holographic images can provide all pictorial cues displayed by current television and film display equipment, although some prototype holographic displays currently provide limited color fidelity, contrast, or detail.

3.1.2. Motion information

Relative movement of objects within a scene can also be used to inform the viewer of scene geometry. In natural viewing, this motion can contain contributions from motion of the viewer relative to the scene, as well as motion of objects in the scene relative to each other.

Relative object motion within a reproduced scene (resulting from either moving objects, or moving camera) can convey information of relative positions and sizes of parts of a scene. These relative motions reveal spatial relationships even when viewed on a traditional two-dimensional television screen. Holographic displays are equally capable of displaying this kind of relative motion.

In natural viewing, movement of the viewer's head can also provide information about scene geometry. Translational head movement allows viewers to discern distance to objects by observing the resulting induced relative motion of the objects viewed. Traditional two-dimensional and stereoscopic three-dimensional displays do not provide this cue to depth. When viewing a two-dimensional display, head motion can produce a distortion of the apparent geometry of the image of the entire scene [4]. Motion also produces the appearance of rigid uniform motion of the entire scene, which provides information about the location of the screen surface, but not about the geometry of the scene. Virtual Environment researchers have sought to overcome this limitation by electronically tracking motion of the head, and adjusting the image displayed accordingly. The addition of correct head-motion parallax to virtual environments has been found, for example, to improve time performance at a tapping task [4] by 12%.

But display changes based on head motion are generally suitable for only a single viewer, and still introduce latency between head motion and screen update [5]. This latency has been shown to degrade performance [6], and research suggests that latency of as little as 8 to 17 milliseconds can be noticed by observers [7]. Full-parallax holographic displays can however present correct pictorial information simultaneously for all eye positions within the viewing zone. Holographic displays are for this reason a natural candidate for tasks that require frequent or rapid viewer motion, and also for tasks that benefit from simultaneous inspection by multiple viewers.

Holographic displays that restrict images to HPO have appearance that can change correctly and instantly for horizontal head motion, but sacrifice correct reproduction of vertical motion parallax. In addition, HPO holograms require assumptions about the location relative to the hologram of the line connecting the viewer's eyes [8]. When viewed from locations increasingly distant from this line, objects in HPO holograms experience increasing amounts of distortion. Head-tracking approaches can adjust the geometry of computer-generated HPO holograms to match viewer head position, but will still introduce delay before correct images are shown under non-horizontal head motion.

3.1.3. Ocular information

Viewers also discern depth information from systems that control muscles in the eyes themselves.

Vergence

When viewing objects or displays, viewers make vergence eye movements that rotate the eyes to bring the images of points in the environment onto corresponding points on the two retinas. Distant objects are best viewed with the eyes both pointing nearly parallel to each other, while viewing close objects binocularly requires crossing the eyes inward. The vergence angle between the two eyes can be used to triangulate the absolute distance to an object. Binocular convergence is most useful as a depth cue for object distances of less than one meter [9]. For objects beyond a few meters, differences in the angle between the axes of the eyes becomes negligible.

Images on traditional two-dimensional displays produce matching images on the two retinas when the lines of sight of the eyes cross at the screen surface. Stereoscopic displays can present different images to each of the eyes, allowing the creation of image pairs that match when the eyes are verged at distances closer or farther than the screen. Vergence angle when fusing a pair of stereo images provides a cue to the absolute distance to the fused objects.

When viewing a holographic display, each of the two eyes captures a different view of the wavefronts reconstructed by the hologram. This allows each eye to receive different images as with a stereoscopic display.

Focus

Viewers actively control the refractive power of their eyes (accommodation) to keep retinal images in focus. Although viewers tend to be poor at using the accommodative state of their eyes alone to accurately gauge distances [10], accommodation can provide information when used in combination with other cues; conversely, when accommodation is not correctly provided by a display the perceptual accuracy of other depth cues can be reduced [11].

Holographic displays, unlike other stereoscopic displays, can present wavefronts that appear in focus at distances in front of, as well as behind the display surface.

Designs for HPO holographic displays often use a vertical diffusing screen to allow images to be viewed from a range of vertical positions [1]. These vertical diffusers have a side effect of creating a single plane of vertical focus for light exiting the display. HPO displays can create image points with controllable horizontal focus, but vertical focus remains fixed at the diffuser. For these displays, scene points in the plane of the diffuser appear to focus and defocus naturally, but points increasingly in front of or behind the diffuser have increasingly astigmatic focus. Viewers have demonstrated the ability to mitigate some of the effects of astigmatic images, adjusting accommodation to compensate for differently oriented targets [12]. Studies evaluating the accommodative state of the eye while viewing images on an HPO holographic display show that viewers can use these images to drive an accommodative response [13]. When viewing HPO holograms from 1100 mm, viewers were able to accommodate equivalently to real-object controls when presented with targets placed up to 450 mm (1.43 Diopters) in front of the hologram plane. Despite these results, the appearance of retinal blur for out-of-focus image points on an HPO display is different than the blur seen in natural scenes, and full-parallax displays. More research is needed to explore perceptual consequences of the scene-dependent astigmatism present in HPO displays.

Holograms are most practically illuminated using one or more monochromatic light sources. This monochromatic illumination may have an impact on viewer's performance at focusing an image. Some research suggests that viewers use chromatic aberration of the eye to inform changes in accommodation, and that viewers accommodate more slowly when viewing objects under monochromatic illumination [14]. Depending on the choice of wavelengths however, a holographic display illuminated by multiple different monochromatic sources would likely allow viewers to once again exploit these aberrations to some extent. Existing displays that use fluorescent, laser, or LED illumination also frequently rely on combinations of narrow-band primary colors. Viewers' general ease at focusing images on these displays suggests that the narrow spectrum of holographic displays will not impose serious constraints.

Ocular Cue Interaction

Vergence and accommodation systems perform best when the cues they provide are in agreement. Stereoscopic displays that can only provide sharp focus at a single plane introduce conflicts between these cues. Since both vergence and accommodation are most active when viewing near scenes, correct presentation of these cues is especially important for images that appear close to the viewer. Although stereoscopic 3D is well suited for theatrical presentation, where images appear at long distances from the audience, home or mobile displays have more strict requirements for conflict-free viewing. Both the relatively small size of current holographic displays, and their ability to correctly reproduce both vergence and accommodation cues suggest that holographic displays will first find adoption for near viewing applications.

3.1.4. Stereopsis

The difference in scene appearance on the retinas of each of the two eyes also plays a role in the perception of depth. This phenomenon is exploited by current stereoscopic 3D displays, showing images captured from two laterally displaced viewpoints, one to each of the viewer's two eyes. Stereopsis takes advantage of the lateral displacements of corresponding points in retinal images of objects. Since eye movements can shift the retinas of the eyes relative to each other, retinal position (and stereopsis) can provide information about relative depth of objects, but not absolute depth [9]. The relative displacements between points in retinal images allow us to triangulate relative distances.

For stereopsis to function, the viewer's eyes must first move to place the image of some object at corresponding points on the two retinas. Parts of objects at similar depths to the fixated point can also be seen clearly, but appearance degrades for objects at distance that produce large disparity in retinal image. Producers of stereoscopic 3D content use knowledge of this phenomenon to predict which parts of a scene will be clearly visible when a viewer is verged on a particular subject. Careful planning of the position of the intended subject relative to the screen can provide more clear and comfortable viewing. Developers of content for HPO holographic displays may need to make similar considerations for managing the depth of the intended subject relative to the screen surface, as HPO displays impose these stereoscopic as well as additional astigmatism-related constraints on clear viewing.

In some wide-angle binocular stereo display configurations, low horizontal resolution of displays has restricted the presentation of stereo images to only two or three distinct planes in depth [4]. Holographic displays, even HPO displays, require high spatial resolution in the horizontal direction, and therefore are unlikely to impose quantization on the stereopsis they can convey.

3.2. Image appearance

When designing holographic displays, aspects of vision relating to laser light and color vision may impose some constraints.

Although the use of coherent light allows the sharpest reproduction of holograms, the images created with coherent light are extremely sensitive to optical imperfections (in any part of the optical system, including the eye). In the presence of these imperfections, laser images appear to be modulated by a sharp, high-frequency speckled texture ("laser speckle") [15]. The appearance of this speckle changes with movement of the eyes, and with constriction and dilation of the pupil. Conventional displays such as projectors that employ laser illumination can also suffer from similar speckle. Techniques for reducing speckle have been employed for these devices **Error! Reference source not found.**, and are applicable to holographic displays as well. Depending on various characteristics of the holographic display, it may be possible to use incoherent light sources like light-emitting diodes instead of lasers.

4. Conclusions

Although holographic displays have potential for providing visual experiences that are far more natural than current "3D," much work must be done in reducing the cost of creating and transmitting content to these displays. Careful consideration of human perceptual capabilities will allow holographic displays to come to market more quickly, allowing for immersive viewing experiences that provide both comfort and realism.

Despite active research on perception relating to displays in general, very little work has been done to explore the viewing of holographic images [17]. Holographic displays have unprecedented potential for reproducing many aspects of natural viewing, but also allow for creation of holograms simulating the constraints of other display systems. As such, holographic displays could be an invaluable tool for basic research in vision science.

As more prototype displays become available, there are increasing opportunities for exploration of applications that take advantage of natural focus, occlusion and motion parallax. The authors see telepresence and teleoperation as application scenarios particularly well suited to these features of holograms [18], and look forward to future work in exploring this potential.

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