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Impact of depth of field simulation on visual fatigue: Who are impacted? and how?☆

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ABSTRACT

While stereoscopic content can be compelling, it is not always comfortable for users to interact with on a regular basis. This is because the stereoscopic content on displays viewed at a short distance has been associated with different symptoms such as eye-strain, visual discomfort, and even nausea. Many of these symptoms have been attributed to cue conflict, for example between vergence and accommodation. To resolve those conflicts, volumetric and other displays have been proposed to improve the user's experience. However, these displays are expensive, unduly restrict viewing position, or provide poor image quality. As a result, commercial solutions are not readily available. We hypothesized that some of the discomfort and fatigue symptoms exhibited from viewing in stereoscopic displays may result from a mismatch between stereopsis and blur, rather than between sensed accommodation and vergence. To find factors that may support or disprove this claim, we built a real-time gaze-contingent system that simulates depth of field (DOF) that is associated with accommodation at the virtual depth of the point of regard (POR). Subsequently, a series of experiments evaluated the impact of DOF on people of different age groups (younger versus older adults). The difference between short duration discomfort and fatigue due to prolonged viewing was also examined. Results indicated that age may be a determining factor for a user's experience of DOF. There was also a major difference in a user's perception of viewing comfort during short-term exposure and prolonged viewing. Primarily, people did not find that the presence of DOF enhanced short-term viewing comfort, while DOF alleviated some symptoms of visual fatigue but not all.

1. Introduction

Stereoscopic displays are no longer the exclusive prerogative of the cinema and research laboratories. People nowadays can afford to buy stereoscopic 3D (s3D) TVs and even stereoscopic monitors, tablets and smart phones. Soon the average user will have an option to choose between 2D and 3D displays for any device they might use. Hence, there is increased interest in developing s3D applications for a variety of displays and devices. It is also important to pay attention to the design of the 3D interface to avoid the issues with quality and perceptual human factors that famously contributed to ending the stereoscopic movie fad of the early- to mid-1950s (Zone, 2007).

Stereoscopic displays spark interest not only among users and developers but also the research community. Over the past few years, extensive research has evaluated different aspects associated with these displays. Yet, many questions remain open, including what types of content are best suited to stereoscopic displays, which tasks benefit the most, how long will the user be able to effectively and comfortably interact with such applications and whether stereoscopic displays can be used effectively by everyone in the general population.

One key problem associated with stereoscopic displays is that stereopsis is only one among many of the cues that help people determine depth. Depth cue omissions can significantly impair depth perception and cause viewers to perceive the observed space flatter than it would appear in real life (Watt et al., 2005; Thompson et al., 2004). So, which cues are missing in typical stereoscopic displays and is it possible to add those cues to improve depth perception?

In real life, the clarity of the retinal image of an object depends on its relation to an eye's fixation in the scene (the POR). In other words, the retinal image for a well-focused eye is the sharpest for objects at the focal distance, and is increasingly blurred as the depth of the object from the focal distance increases (Gullstrand, 1910).

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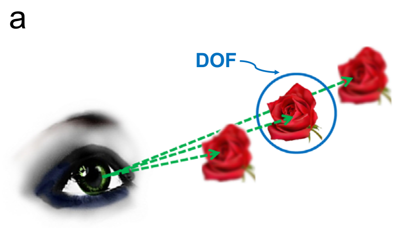
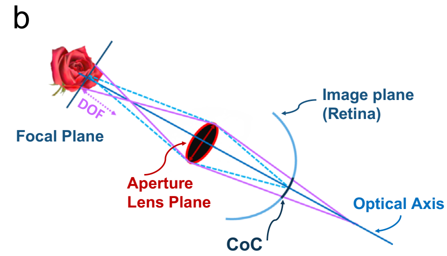


Depth of Field as perceived by an observer.



Depth of Field Geometry: the formation of the image on the retina.

Fig. 1. Depth field: Field. (a) Depth of Field as perceived by an observer. (b) Depth of Field Geometry: the formation of the image on the retina.

The cornea provides most of the optical power contributing to image formation in the eye but the cornea has a fixed focal length. To focus on the POR, the eye must adjust the shape of its intraocular lens to bring objects nearer than infinity into sharp focus; this process is known as accommodation. The ciliary muscles are responsible for adjusting the shape of the lens to accommodate the eye on an object of interest. Conversely, accommodation provides a physiological cue to the distance of an object: by monitoring the focal state associated with the fixated object the observer could obtain an estimate of the distance of the object. Accommodation is a distance cue that usually is not accounted for in stereoscopic displays. While it is possible to provide this cue to an observer in virtual reality, this requires special volumetric displays. Such displays present targets at different optical distances, for instance by displaying graphics on multiple planes at a variety of optical distances (Sucharov, 1998; Suyama et al., 2000; Akeley et al., 2004).

Although, accommodation provides information concerning the distance of the fixated object, it does not provide static information about depth between objects in the display (although change in accommodation across fixations could be informative). However, when the eye accommodates at a given distance, objects that are nearer or further will be subject to defocus blur and image blur is an informative depth cue (Nguyen et al., 2005; Held et al., 2012). In contrast to the real world, most 2D and 3D graphical applications do not render selective image blurring. Movies, games, and still photography do, but frequently for artistic reasons rather than realistic simulation and, in these cases, the blur is determined by the camera's focus not the eye's focus.

The range of distances where objects are perceived to be in focus for an imaging system such as the human eye is typically referred to as the *depth of field* (DOF) (Fig. 1). In 2D photography, the extent of the DOF is determined by the circle of confusion (CoC), which is a blur circle in the image plane (retina for the human eye). The size of CoC depends on size of the aperture (pupil) and the depth relative to the focal plane. As depth increases, the blur due to the CoC eventually becomes detectable (according to some criterion). Hence, the depth of field depends on both the CoC and the resolution of the sensor (visual acuity of the eye). The border of the CoC is not distinct in a real eye but the CoC is a useful model of DOF. The diameter of the CoC (b) can be approximated by different models. For example, Pentland (1987) used a thin-lens model to describe b as follows:

$$b = A\frac{s_0}{d_0}\left|1 - \frac{d_0}{d_1}\right|$$

where A is the pupil diameter, s_0 is the distance from the lens to the retina, d_0 is the distance from the lens to the focal plane and d_1 is the distance from the lens to another object, whose image forms behind an image plane. Consequently, image blur due to lens defocus can be simulated by calculating blur circles for different objects. By adding DOF to 2D displays, one can contribute to depth perception and improve depth qualitatively (Mather, 1997; Vinnikov and Allison, 2014). In addition, Mauderer et al. (2014) found that gaze-contingent DOF increased perceived realism in 3D images.

Accommodation and defocus blur are less important for the cinema as they are effective cues to distance only for relatively near targets, say less than two meters away. Presentation of such images in the cinema is rare since these would correspond to objects presented at extreme depths with respect to the screen. However, smaller stereoscopic displays are typically viewed at closer distances. In a such scenario, people often rely on an additional distance cue, which is *vergence*. Vergence is a physiological distance cue associated with the movements of the eyes. In vergence, the two eyes rotate in opposite directions. A principal function of vergence is to align the high-resolution fovea of both eyes on a target of interest to get a sharp binocular image of the object. As a result, observers need to increasingly cross, or converge, their eyes as the distance to an object of interest decreases. Typically, convergence and accommodation are tightly coupled (Schor, 1979). However, this is not the case for stereoscopic displays. The problem arises from the fact that, when an observer views a stereoscopic 3D display, she needs to converge her eyes to fuse stimuli located off the screen, while accommodating her eyes at the screen distance. This is known as an *accommodation-vergence conflict* (Fig. 2). This conflict can lead to a range of negative side effects, such as discomfort, eye-strain, headache, and visual fatigue (Luebke, 2003; Mon-Williams and Wann, 1998; Wann et al., 1995; Lambooij et al., 2009; Hoffman et al., 2008). One solution is to try to null the conflict by a quickly adjusting binocular disparities to keep objects of interest near the screen plane (Bernhard et al., 2014). However, as with accommodative displays, such a solution is often limited by the number of discrete physical screens (leading to a limited number of real distances). Such displays also cause unnatural shifting of the rendered scene relative to the screen as points of interest change. Finally such accommodation displays have noticeable artefacts associated with fast disparity adjustments. Hence, a possible solution to alleviate the impact of the negative side effects is to provide an artificial simulation of defocus blur (Brooker et al., 2001; Villarruel, 2006). This would not resolve the accommodative-vergence conflict but would provide the natural relationship between retinal image blur and binocular disparity.

Such an approach requires an invisible user interface that responds to the user's action, in this case their gaze movements, in real-time without any explicit user intent. In order to provide the blur cues present in the real world, the interface needs to measure the POR and update the display in a naturalistic fashion. Ideally, such a simulation will provide a more natural and comfortable interface that users could tolerate for reasonably long periods of intensive use. A DOF simulation has to be congruent to the user's