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Augmented reality as a tool for studying visual plasticity: 2009 to 2018

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Abstract

Augmented reality (AR) has developed rapidly since its conception less than 30 years ago, and is now a “hot topic” for both consumers and scientists. While much attention has been paid to its application in industry, medicine, education and entertainment, AR’s use in psychological research has been less noted. This paper surveys recent progress in basic research that uses AR to explore the plasticity of the adult visual system. We focus on a particular application of AR called “altered reality”, which has been used to shed new light on mechanisms of long-term contrast adaptation and ocular dominance plasticity. These results suggest that AR could additionally be a useful tool for treatment of visual disorders.

Keywords: Augmented reality, altered reality, visual plasticity, contrast adaptation, ocular dominance

The term “augmented reality” (AR) was first coined in the 1990s by Caudell and Mizell (Caudell & Mitzell, 1992). In contrast to virtual reality (VR) that completely immerses a user inside a computer-generated virtual environment, AR is a technology in which virtual objects are superimposed upon or composited with the real world, so that the user can see or interact with them. Over the past few decades, AR has rapidly developed and been applied to many different domains, including personal information assistance, navigation, medicine, education, and entertainment. These uses of AR have received substantial attention in the public media.

As a timely complement, the present article reviews the use of AR in basic research, focusing on studies of visual plasticity. The visual system can change its function in response to environmental demands, and two lines of research have demonstrated this: learning of specific tasks ("perceptual learning"), and effects of sustained exposure to a particular visual feature ("adaptation", for reviews see (Basgoze, Mackey, & Cooper, 2018; Maniglia & Seitz, 2018; Shibata, Sagi, & Watanabe, 2014; Webster, 2015)). Past adaptation work generally displayed stimuli on monitors. However, some more recent work has used AR (Zhang, Bao, Kwon, He, & Engel, 2009) to investigate a series of questions regarding visual plasticity.

Why Use AR in Research of Visual Plasticity?

A traditional way to improve vision is perceptual training, which can produce large benefits for a wide variety of tasks in adults (Karni & Sagi, 1991; Shibata et al., 2014). However, the effects of perceptual learning are often limited to the trained stimulus (Bao, Yang, Rios, He, & Engel, 2010; Karni & Sagi, 1991; Schwartz, Maquet, & Frith, 2002), but see (Xiao et al., 2008). Especially large amounts of training ("overtraining"), potentially required to produce plasticity in earlier stages of visual processing, may show particularly high specificity (Sagi, 2011). Accordingly, some researchers have adopted a complementary approach— allowing observers to perform everyday tasks in an environment that places demands upon mechanisms of plasticity. This long-term adaptation approach has been enhanced by the development and use of AR.

AR Displays

AR systems have been developed with three different presentation methods. In video see-through, video images of the world are captured digitially, combined with additional digital content, and the result is presented on a head-mounted (HMD) or hand-held video display. In optical see-through, digital content is superimposed via transparent displays on a "direct" view of the world, not digitally captured, but potentially processed via optics. In projective displays digital content is displayed on real world objects using video projectors, and the scene is viewed naturally.

Optical see-through is often seen in both commercial (e.g. Google Glass) and clinical applications, for example augmented-vision devices to aid patients with peripheral vision loss (Peli, Luo, Bowers, & Rensing, 2007)). As early as 1992, video see-through was used to study visual adaptation to reverse contrast ("negative") images (as seen through the viewfinder of a video camera (Anstis, 1992)). Recent AR-based visual plasticity studies have used the HMD-based video see-through method. Unlike the typical method, in which digital content is overlaid upon the camera video of the world, in visual plasticity studies global image processing is applied in real-time to the entire video to alter some feature of the images (Bai, Dong, He, & Bao, 2017; Bao, Dong, Liu, Engel, & Jiang, 2018; Bao & Engel, 2012; Grush, Jaswal, Knoepfler, & Brovold, 2015; Haak, Fast, Bao, Lee, & Engel, 2014;

Schweinhart, Shafto, & Essock, 2017; Zhang et al., 2009).

This type of manipulation has been termed *altered reality*. The primary advantage of this approach is its flexibility, since the viewed display is entirely digital, custom computer programs can easily remove, add, or modify many different features of visual input. The disadvantages are the limits in spatial resolution, field of view, and updating speed that real-time image processing imposes.

Using Altered Reality to Study Long-term Contrast Adaptation

The visual system adapts to changes of the visual environment over timescales spanning many orders of magnitude (Webster, 2015). Very long-term adaptation has been studied for more than a century, beginning with George Stratton's pioneering work investigating multiple days of adaptation to inverting prisms (Stratton, 1897). Prisms and spectacles remain useful tools to this day for studying long-term visual adaptation (Kwon, Legge, Fang, Cheong, & He, 2009; Neitz, Carroll, Yamauchi, Neitz, & Williams, 2002; Tregillus, Werner, & Webster, 2016; Yehezkel, Sagi, Sterkin, Belkin, & Polat, 2010).

However, optical methods are limited in the kinds of image transformations they can compute. Thus it is difficult to use them to change the statistics of the environment in complex ways. For example, while it is easy to remove high spatial frequency information with lenses that blur the image, removing a mid-range band of spatial frequencies is impossible with conventional optics.

While some studies have presented processed information on video screens (Falconbridge, Wozny, Shams, & Engel, 2009), the full altered reality technique allows subjects to interact with the environment freely. This makes it possible to investigate adaptation at relatively long timescales. The first work using a head-mounted display was published in 2009, and measured effects of depriving the visual system of vertical information (Zhang et al., 2009). Video frames from a head-mounted camera were filtered in real time, using a simple multiplicative filter in the Fourier domain, and then displayed (see Figure 1). Viewing this altered reality for 4 hours increased observers' sensitivity to the deprived orientation (Zhang et al., 2009).

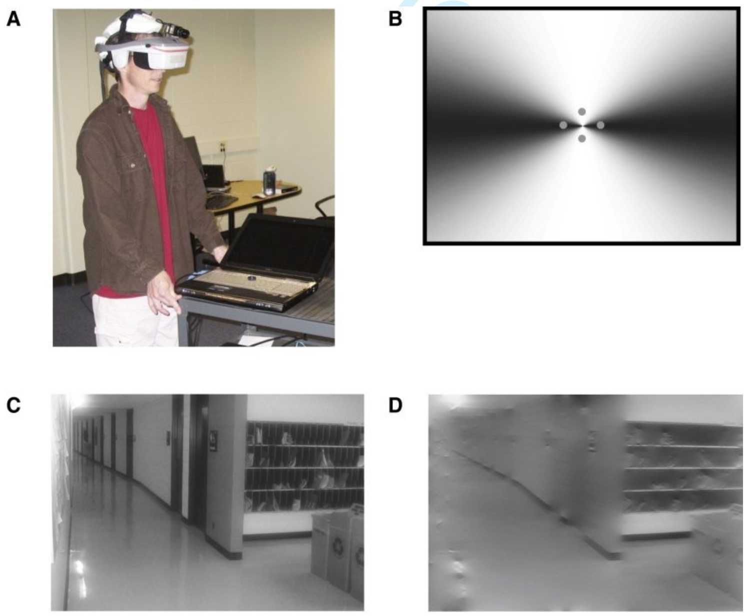

Figure 1. (A) In several of the studies reviewed here (Bao & Engel, 2012; Haak et al., 2014; Zhang et al., 2009), subjects wore a head-mounted display and a video camera. The camera streamed video to a laptop computer where the images were filtered and displayed on an HMD.

Subjects could engage in many everyday activities, such as eating, walking, watching movies, and playing video games. (B) The filter is shown in the Fourier domain, where orientation is indicated by polar angle and spatial frequency is indicated by distance from the center of the image. Black colors show where the filter passed zero energy and are centered on vertical orientations (along the x axis by convention). Dots indicate the frequency and orientation of test stimuli used in Zhang et al., 2009. (C and D) Sample intact and filtered images. Adapted from (Zhang et al., 2009) © Elsevier Inc.

Subsequent studies measured the effects of adaptation for a range of durations (Bao & Engel, 2012; Haak et al., 2014). Bao and Engel (2012) found that the effects of adaptation gradually increased in strength and duration over a range of durations from 1 minute to 8 hours. Haak et al. (2014) showed that effects continued to grow stronger and longer lasting for durations up to 4 days. For the visual system to control adaptation over all these durations, it seems likely that distinct mechanisms operate at different timescales.

One prediction of this multiple-mechanism theory is the presence of a spontaneous reemergence of residual effects of long-term adaptation following a short-term deadaptation which cancels the long-term effects. Such “spontaneous recovery” of long-term aftereffects has been observed in a number of studies covering many different types of visual adaptation (Bao & Engel, 2012; Bao, Fast, Mesik, & Engel, 2013; Haak et al., 2014; Mei, Dong, Dong, & Bao, 2015; Mei, Yuan, Liu, Pan, & Bao, 2018; Mesik, Bao, & Engel, 2013). It appears to be a general rule in the visual system that multiple distinct mechanisms control visual adaptation over different timescales, that can range from milliseconds to days.

More subtle manipulations of the environment have also been explored recently (Schweinhart et al., 2017). Natural images contain the most content around horizontal orientations, the second most around vertical, and the least near oblique (±45°). Correspondingly, when matching the perceived salience of a reference pattern, observers perceive a horizontal test pattern as least salient and oblique pattern as strongest. Schweinhart et al. (2017) used AR to place subjects for 2 hours in a world in which images had equal amounts of content (formally, Fourier energy) at all orientations and at each spatial frequency. This exposure reduced the horizontal effect, suggesting that observers adjusted the salience of orientations dependent upon recent experience.

Using Altered Reality to Study Ocular Dominance Plasticity

Monocular Deprivation

Usually, one of humans' two eyes is stronger than the other. It has long been known that ocular dominance at the neural level is developed and formed during the critical period after birth, and remains stable during adulthood (Wiesel & Hubel, 1963).

Recent work, however, has revealed that perceptual ocular dominance in adult humans can be reshaped via several hours of monocular deprivation (Lunghi, Burr, & Morrone, 2011). Visual inputs from one eye were blocked by an eye patch, and perceptual dominance was measured with the binocular rivalry task, where dissimilar images were presented to the two eyes, resulting rivalrous perception of the two images in alternation. The stronger an eye is, the more often the image presented to that eye is perceived. Lunghi et al. found that after 2.5 hrs patching, adult human subjects perceived the image presented to the patched eye more frequently (Lunghi et al., 2011; Lunghi, Burr, & Morrone, 2013). This suggests that monocular deprivation increased the perceptual dominance of the deprived eye.

Perceptual ocular dominance is usually defined as one eye being dominant in certain behavioral tasks, such as binocular rivalry or interocular contrast integration. Another form of ocular dominance, "sighting dominance" relates to which eye is used to foveate targets; its relation to perceptual dominance remains unclear, and the neural bases of both are not completely understood. Nevertheless, Lunghi et al.'s results make clear that adult binocular interactions are highly plastic at some level.

Lunghi et al.'s (2011) conclusion received supports from other work adopting a different psychophysical test—binocular phase combination (Zhou, Reynaud, & Hess, 2014). Unlike binocular rivalry, the stimuli in this task are two dichoptically presented horizontal gratings that differ only in spatial phase. The similarity between stimuli in the two eyes allows subjects to experience a fused (or integrated) grating. The perceived phase of the fused grating depends on the strength of the neural responses to each monocular grating. In general, its perceived phase is closer to that of the grating presented to the stronger eye.

Relying on this test, Zhou and colleagues (2014) explored the aftereffects following 2.5 hours of adaptation using an HMD-based setup. Observers viewed movies on an HMD, which allowed presentation of an intact movie to one eye and an image processed movie to the "deprived" eye. They found a significant shift in perceptual ocular dominance when the deprived eye viewed low contrast or low-pass filtered movies. These results suggest that the interocular imbalance of contrast energy and especially the high spatial frequencies in the amplitude spectrum is critical for driving the aftereffects of monocular deprivation.

Zhou et al. (2014) did not observe significant changes of perceptual ocular dominance when the deprived eye viewed "phase-scrambled" movies. This manipulation leaves the Fourier amplitude spectrum of the input image alone but randomizes its Fourier phase information. These results suggested that phase information was not important in perceptual ocular dominance plasticity. However, different results were found when perceptual dominance was measured with a binocular rivalry task (Bai et al., 2017), in a study that also replicated the lack of an effect for binocular phase combination. These results indicate that the two measurements are likely supported by different neural mechanisms, and that monocular deprivation of Fourier phase information alone can be sufficient to induce a shift of eye dominance. A number of additional papers from the groups of researchers cited above have examined effects of long-term adaptation on ocular dominance plasticity (most reviewed in Basgoze, Mackey, & Cooper, 2018). We have limited our review to key results using AR.

Figure 2. The altered reality system in Bai et al.'s (2017) work. Subjects wore the HMD during adaptation. The computer processed the images taken by the camera in real-time, and then presented the images to the HMD. The original image was presented to one eye, while a phase-scrambled image was presented to the other eye. The small LCD monitor shows what the subject is viewing. Adapted from (Bai et al., 2017) © Elsevier Inc.

Treating Amblyopia with AR

The visual disorder called amblyopia (also known as "lazy eye") is characterized by extreme ocular imbalance. Amblyopia is present in about 2-3% of the population, and people with amblyopia have very poor visual acuity and contrast sensitivity in the non-dominant, amblyopic eye. Amblyopia also leads to impairment or absence of stereopsis. It is traditionally treated by patching the fellow eye, pharmacologic penalization of the fellow eye, or a combination of these. Patching is generally most effective during childhood (Holmes, Repka, Kraker, & Clarke, 2006), leaving a shortage of treatments for adults.

Over the past twenty years, researchers tested the effectiveness of perceptual learning to treat amblyopia (for review, see (Basgoze et al., 2018)), including both monocular training (Levi & Polat, 1996) and dichoptic training (Hess, Mansouri, & Thompson, 2010). Recent work has suggested that dichoptic training induces greater level of plasticity than monocular training (Li et al., 2013; Liu & Zhang, 2017). However, perceptual learning relies on training with specific tasks in the laboratory. Frequent training sessions can be difficult to integrate into patients' life and work, which limits compliance, and which may have reduced its effectiveness in a large clinical trial (Gao et al., 2018). In addition, too much training, "overtraining" may limit transfer of perceptual gains to general vision outside the task (Sagi, 2011).

To overcome some of these challenges, AR was recently used to study ocular dominance plasticity and treat patients with amblyopia (Bao et al., 2018). Observers adapted to complementary patchwork video images presented to each eye: Camera images were divided into squares following a grid, and each square was randomly assigned to be displayed intact to one eye, while in the other eye the corresponding square was filled with its mean color. Viewing these images forced the visual system to weight the input from each eye equally in order to process the complete scene.

Five days of adapting to patchworks for a few hours each day increased interocular balance, as measured with binocular rivalry, in non-amblyopic observers who had relatively imbalanced eyes. Two other experiments showed that repeated patchwork adaptation produced gains in visual function in adults who were formally diagnosed with amblyopia, improving visual acuity in the amblyopic eye, along with other measures of binocular function (Bao et al., 2018).

Conclusions

By allowing observers to interact with systematically altered worlds, AR has extended studies of visual adaptation to durations of hours and days. This enabled systematic investigations of long-term visual adaptation that are difficult to realize with traditional approaches.

The methods described here can be extended in many directions. Future work could apply AR to study plasticity in the perception of other visual qualities, such as motion or color (Grush et al., 2015). It would also be useful to incorporate neuroimaging techniques into AR rigs, to allow continuous measurement of the neural changes that produce long-term adaptation (Engel, Mesik, & Vergeer, 2018). AR also provides a natural way to study long-term plasticity of interactions between the senses (Bai, Bao, Zhang, & Jiang, 2019).

AR technology continues to improve rapidly, with both cameras and head mounted displays becoming lighter and higher resolution, and image processing hardware showing parallel gains. We expect the potential scientific value of AR to also rise in the future.

Recommended Readings

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[•*A clearly written and relatively comprehensive review for readers who wish to expand their knowledge on augmented reality*]

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[•*A clearly written, short, and relatively comprehensive review for readers who wish to expand their knowledge on altered reality*]

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to the authorship or the publication of this article.

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