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MONOCULAR DEPRIVATION OF FOURIER PHASE INFORMATION BOOSTS THE DEPRIVED EYE'S DOMINANCE DURING INTEROCULAR COMPETITION BUT NOT INTEROCULAR PHASE COMBINATION

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Abstract—Ocular dominance has been extensively studied, often with the goal to understand neuroplasticity, which is a key characteristic within the critical period. Recent work on monocular deprivation, however, demonstrates residual neuroplasticity in the adult visual cortex. After deprivation of patterned inputs by monocular patching, the patched eye becomes more dominant. Since patching blocks both the Fourier amplitude and phase information of the input image, it remains unclear whether deprivation of the Fourier phase information alone is able to reshape eye dominance. Here, for the first time, we show that removing of the phase regularity without changing the amplitude spectra of the input image induced a shift of eye dominance toward the deprived eye, but only if the eye dominance was measured with a binocular rivalry task rather than an interocular phase combination task. These different results indicate that the two measurements are supported by different mechanisms. Phase integration requires the fusion of monocular images. The fused percept highly relies on the weights of the phase-sensitive monocular neurons that respond to the two monocular images. However, binocular rivalry reflects the result of direct interocular competition that strongly weights the contour information transmitted along each monocular pathway. Monocular phase deprivation may not change the weights in the integration (fusion) mechanism much, but alters the balance in the rivalry (competition) mechanism. Our work suggests that ocular dominance plasticity may occur at different stages of visual processing, and that homeostatic compensation also occurs for the lack of phase regularity in natural scenes. © 2017 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: ocular dominance, monocular deprivation, fourier phase, binocular rivalry, interocular phase combination.

INTRODUCTION

A classical model for neuroplasticity is ocular dominance plasticity. To date, mounting evidence has demonstrated residual ocular dominance plasticity in the adult visual system (Xu et al., 2010a; Lunghi et al., 2011, 2013; Ooi et al., 2013; Zhou et al., 2013, 2015; Lo Verde et al., 2017), which is conventionally thought to be hardwired (Wiesel and Hubel, 1963; Hubel and Wiesel, 1970).

There is a long history of using monocular deprivation to study ocular dominance plasticity. During deprivation, no pattern information is transmitted through the eye patch. In vision research, it is widely accepted that the early visual neurons could be considered as "Fourier filters", analyzing the amplitude and phase of the input images (Schade, 1956; Campbell and Robson, 1968; Graham and Nachmias, 1971; Westheimer, 2001). In accordance with this notion, monocular deprivation blocks both the Fourier amplitude and phase information from entering the patched eye. In the signal processing literature, phase has long been realized to be more important than amplitude in image reconstruction and scene recognition (Oppenheim and Lim, 1981; Piotrowski and Campbell, 1982; Ni and Huo, 2007). Naturally, a question arises: what is the consequence of depriving the Fourier phase information alone, will the eye dominance be altered?

One way to answer this question is to test whether the eye dominance shifts or not after one eye is deprived of the phase-aligned frequencies describing contours and higher level spatial representations, on the premise that the Fourier amplitude spectra of the visual inputs remain identical across the two eyes. Note that while the global average power of the phase-scrambled stimuli is the same as the original, locally there are important differences, and this defines the features (Morrone and Burr, 1988). Therefore, a decoder could pick the difference easily (Perna et al., 2005, 2008; Castaldi et al., 2013).

Notably, a recent study (Zhou et al., 2014) has attempted to test whether the deprivation of phase regularity may alter the eye dominance. In their work, the two eyes see the same movie except that in one eye the Fourier phase spectrum of the input is scrambled. By using an interocular phase combination task (Ding and Sperling, 2006; Huang et al., 2010; Kwon et al., 2014), they found no change of eye dominance after watching the movie for 2.5 h. However, in Lunghi et al.'s

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Abbreviations: ANOVA, analysis of variance; HMD, head-mounted display.

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(2011) monocular patching study, the eye dominance is measured with binocular rivalry, another method frequently used to evaluate eye dominance (Ooi and He, 2001; Handa et al., 2004, 2005; Lunghi et al., 2011, 2013; Xu et al., 2011; Platonov and Goossens, 2014; Dieter and Blake, 2015). The use of different measurements makes it difficult to compare the two studies directly. Since it is possible that the two measures are supported by different mechanisms, eye dominance measured with phase integration and binocular rivalry (competition) may reach different conclusions. Therefore, without stricter experimental control, one cannot affirmatively conclude whether the monocular deprivation of phase information can reshape the eye dominance like monocular patching. In the present study, we therefore adopted both the binocular rivalry and interocular phase combination tasks to measure the eye dominance prior to and following the simulated monocular patching and monocular deprivation of phase regularity. Such a more complete design allowed us to examine a possibility that the monocular deprivation of phase regularity alone may lead to changes in eye dominance, but only when measured with direct inter-ocular competition rather than inter-ocular phase combination. Besides, Zhou and colleagues' (2014) negative results derive from the observations of only three subjects, it remains appealing to re-examine this question in a larger amount of subjects for stronger statistical power.

To achieve the monocular deprivation of phase regularity, we developed an "altered reality" system, with which subjects could interact with the natural world that had been changed through real-time image process. For 3 h, one eye's inputs were replaced with spatially correlated (or "pink") noises (see Method). Instead of off-line image processing (Zhou et al., 2014), our method realizes the phase scrambling in real-time, and guarantees identical amplitude spectra in both eyes by strictly preserving the complex conjugations of the Fourier transforms throughout adaptation.

Besides a possible null effect that Zhou et al. have reported (Zhou et al., 2014), two distinct positive results might be observed. First, if monocular deprivation of phase regularity shifts the eye dominance to the deprived eye, sharing mechanisms may underlie the phase deprivation and patching. Instead, if deprivation increases the eye dominance of the non-deprived eye, we would speculate that a later mechanism selectively promotes the signal transmission pathway for the non-deprived eye because of its superior signal-to-noise ratio. Through three experiments, our results showed significant shift in eye dominance to the deprived eye when the eye dominance was measured with a binocular rivalry task. We also replicated Zhou et al.'s (2014) null effect when measuring the eye dominance with an interocular phase combination task.

EXPERIMENTAL PROCEDURES

Experimental procedures for all the experiments of the present study were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. Informed consents were obtained from all the subjects. All the experiments described have been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

Comparing monocular phase regularity deprivation with patching (Experiment 1)

Participants. Twelve subjects (11 females; age: 19–25 years old) participated in Experiment 1. All were naive to the experimental hypotheses, and had normal or corrected-to-normal vision.

Apparatus. Binocular rivalry measurements were conducted on a Dell OptiPlex 7010 computer using MATLAB and Psychtoolbox 3.0.11 Extensions (Brainard, 1997). Stimuli were presented on a 27.2-inch LCD monitor (Asus VG278HE, 1920 × 1080 pixel resolution at the refresh rate of 120 Hz), and viewed through a pair of shutter goggles (NVIDIA 3D Vision2 P1431). The monitor was calibrated with a spectrophotometer (Photo Research, PR-655) with the sensor attached behind the shutter goggles. To calibrate the display, we measured the luminance gamma curves and inverted them with a look-up table. The mean luminance of the monitor was 48.68 cd/m^2, but reduced to 18.76 cd/m^2 when viewed through the shutter goggles. Participants viewed the stimuli through the shutter goggles in a dark and quiet room from a distance of 100 cm. A chin-rest was used to help minimize head movement.

We developed two altered reality systems for the present study (see Fig. 1). Each system comprised of a camera (The Imaging Source) connected to a computer that feeds into a head-mounted display (HMD). One system was equipped with a DFK-23UM021 USB3.0

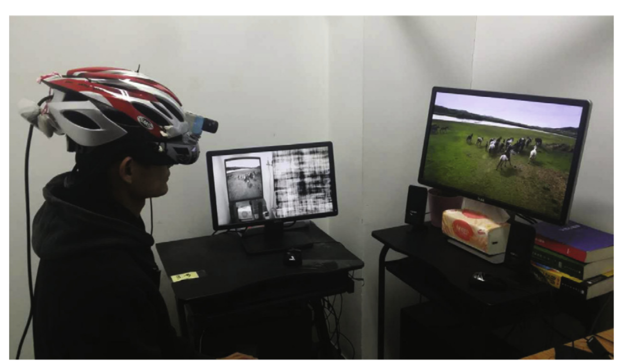

Fig. 1. The alter reality system and an example of the experimental scene. The system comprised of a camera connected to a computer that fed into the HMD. This computer processed the images taken by the camera in real-time, and then presented the images to the HMD. The original image was presented to one eye, while the altered image to the other eye. Participants wore the HMD during adaptation when they could view the world freely or watch movies as shown in the figure. The small LCD monitor was also connected to the computer, which worked in a clone mode with the HMD. This enabled the experimenters to see what the subject viewed. In this example, the subject was watching the original camera video through the left eye, and the pink noise video through the right eye.