Attention Enhances Short-Term Monocular Deprivation Effects

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Abstract

Short-term occlusion of one eye in adults can enhance the ocular dominance of that eye, a phenomenon known as the short-term monocular deprivation effect. Recent findings have revealed that in certain adaptation paradigms with balanced binocular input, eye-based attention can shift ocular dominance toward the unattended eye. Since monocular occlusion blocks all input to one eye, attention is presumably allocated to the fellow eye. Consequently, it has been hypothesized that the short-term monocular deprivation effect may also be modulated by eye-based attention, though empirical evidence remains lacking. In the present study, participants performed an attentional tracking task while undergoing monocular deprivation via eye patching. Ocular dominance changes were measured using binocular rivalry before and after a one-hour tracking task. The results demonstrated that when the test gratings in the binocular rivalry task shared visual features with the target gratings in the tracking task, the deprivation effect was of greater magnitude; conversely, when the test gratings shared features with the distractor gratings, the deprivation effect was relatively diminished. This finding provides the first evidence that attention can enhance the short-term monocular deprivation effect.

Full Text

Attention Enhances Short-Term Monocular Deprivation Effect

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Abstract

Briefly patching one eye in adults has been found to enhance that eye's dominance, a phenomenon known as the short-term monocular deprivation effect. Recent studies have discovered that in certain adaptation paradigms with balanced binocular input, eye-based attention can shift ocular dominance toward the unattended eye. Since monocular patching blocks all input from one eye, attention is inevitably allocated to the other eye. Therefore, the short-term monocular deprivation effect is hypothesized to be potentially modulated by eye-based attention as well, though empirical evidence remains lacking. In the present study, participants performed an attentional tracking task while undergoing monocular deprivation. Ocular dominance was measured with binocular rivalry before and after one hour of tracking. Results showed that the deprivation effect was larger when the test gratings in the binocular rivalry task shared visual features with the target gratings in the tracking task, and smaller when they shared features with the distractor gratings. These findings provide the first evidence that attention can enhance the short-term monocular deprivation effect.

Keywords: monocular deprivation, ocular dominance, attention, binocular rivalry

Ocular dominance plasticity is a classic model for studying experience-dependent brain plasticity. Since the 1960s, it has been well established that depriving one eye of visual input during a postnatal critical period can induce long-lasting structural and physiological changes in visual cortex (Wiesel & Hubel, 1963). However, recent research indicates that ocular dominance plasticity is not limited to the critical period (Lunghi et al., 2011). In that study, perceptual ocular dominance was measured using a binocular rivalry task, in which two different images presented to corresponding retinal locations compete for conscious awareness. The results demonstrated that after 2.5 hours of monocular deprivation, adult participants perceived the deprived eye's image more frequently, indicating a shift in ocular dominance toward the deprived eye (Lunghi et al., 2011). This effect, later termed short-term monocular deprivation, has received extensive attention over the past decade (Binda et al., 2018; Lunghi, Berchicci, et al., 2015; Lunghi et al., 2013; Lunghi, Emir, et al., 2015; Min et al., 2018; Song, Wang, et al., 2023; Virathone et al., 2021; Zhou et al., 2015; Zhou et al., 2014).

To further understand the mechanisms underlying this ocular dominance plasticity, researchers have explored various forms of monocular deprivation beyond simple patching (Bai et al., 2017; Lyu et al., 2020; Wang et al., 2017; Yao et al., 2017; Zhou et al., 2014). Altering low-level visual input properties—including energy information (e.g., contrast within certain orientation or spatial frequency ranges) and phase information (e.g., contours) of monocular images—can also produce significant shifts in ocular dominance toward the deprived eye. Based on these findings, the short-term monocular deprivation effect is thought to originate primarily in early visual cortex, a view supported by neurophysiological and neuroimaging studies (Binda et al., 2018; Lunghi, Berchicci, et al., 2015; Zhou et al., 2015).

In addition to the typical short-term monocular deprivation effect, recent research on long-term, eye-based attention has reported a surprising new form of ocular dominance plasticity (Song, Lyu, & Bao, 2023; Song, Lyu, Zhao, et al., 2023; Wang et al., 2021). Specifically, when visual input is balanced across the eyes, manipulating attention toward one eye can reshape ocular dominance after a period of adaptation. This manipulation can be achieved by having participants wear a prism that inverts the image in one eye (Wang et al., 2021), or by presenting normal movie clips to one eye while showing the same clips played in reverse to the other eye (Song, Lyu, & Bao, 2023; Song, Lyu, Zhao, et al., 2023).

The discovery that eye-based attention itself can alter ocular dominance opens new possibilities for investigating how high-level cognitive processes influence ocular dominance plasticity. Given that attention should be biased toward the non-deprived eye during monocular deprivation, an intriguing question arises: Does attention also affect the typical short-term monocular deprivation effect? This is a novel question because typical monocular deprivation removes all or part of monocular input, whereas in eye-based attention studies, basic features and contour information are preserved and balanced across eyes (Song, Lyu, & Bao, 2023; Song, Lyu, Zhao, et al., 2023; Wang et al., 2021). One might argue that holistic processing of faces and biological motion configurations in the non-attended eye could be disrupted when using inverted prisms (Wang et al., 2021). However, this is not the case in the reversed-video adaptation paradigm (Song, Lyu, & Bao, 2023; Song, Lyu, Zhao, et al., 2023). Consequently, these two adaptation paradigms cannot be simply regarded as typical short-term monocular deprivation, and findings from eye-based attention studies may not directly answer whether attention influences the typical short-term monocular deprivation effect.

We note that one recent study has attempted to address this question (Chen et al., 2020). During monocular deprivation, participants were asked to play an action video game with sound, watch a silent replay of the same action game, or play a non-action video game. However, no significant differences in ocular dominance shifts were found across these three conditions, leading the authors to conclude that the short-term monocular deprivation effect is not influenced by attention. We caution against drawing strong conclusions from this null result, as their experimental approach may have several limitations. First, they did not directly assess attentional levels across the three conditions. Second, they used a binocular phase combination task rather than a binocular rivalry task to measure ocular dominance. Previous research has shown that short-term monocular deprivation effects measured with these two tasks are not always consistent (Bai et al., 2017).

To address these potential issues, we designed a novel experimental task to strictly control participants' visual attention during monocular deprivation. Specifically, while one eye was patched, participants performed a visual attention tracking task on one of two sets of gratings. The target and distractor gratings in the tracking task had distinct basic visual features and also served as test stimuli in the binocular rivalry task before and after deprivation. We hypothesized that if attention can modulate short-term monocular deprivation, the shift in ocular dominance would be more pronounced when the test gratings shared features with the target gratings during patching. Furthermore, whereas Chen et al. (2020) manipulated attention across different deprivation sessions, our manipulation of attentional level could be implemented within a single deprivation period, potentially avoiding interference from fluctuations in the monocular deprivation effect across sessions.

2.1 Participants

Twenty participants (4 males, 16 females, aged 18–28 years) took part in the experiment. Sample size was determined based on previous studies in this field (Binda et al., 2018; Lyu et al., 2020; Menicucci et al., 2022; Virathone et al., 2021). All participants had normal or corrected-to-normal vision and provided informed consent before the experiment. None were aware of the experimental purpose. The study complied with the ethical standards of the Declaration of Helsinki and was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Apparatus

The experimental program was written using MATLAB 2021a with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on a DELL P1230 CRT monitor (resolution: 1600\$×1200, $refreshrate : 75Hz).ThemonitorwascalibratedusingaPhotoResearchPR-655photometer, withameanluminanceof44.7cd/$
The experiment was conducted in a dark room. Participants viewed the monitor through a stereoscope at a viewing distance of 70 cm. A chinrest was used to minimize head movements.

2.3.1 Practice Phase Binocular Rivalry Task

In the practice phase, binocular rivalry stimuli consisted of two orthogonal sinusoidal gratings (diameter: 1°, spatial frequency: 2 cpd, Michelson contrast: 80%) with edges blurred by a Gaussian filter. Grating orientations were \$$\pm 45°.Thegratingswerepresentedcentrallytoeacheye.Topromotestablebinocularfusion, acentralredfixation$
$0.07°)andahigh - contrastcheckerboardframe(size :$ 2.5°×\$2.5°, thickness: 0.25°) were also presented to both eyes.

Each trial lasted 60 seconds: 5 seconds of blank screen followed by 55 seconds of grating stimulation. Once the gratings appeared, participants were instructed to fixate on the red point and press corresponding keys (right arrow, left arrow, or down arrow) based on their perceived orientation (45°, –45°, or a mixture of both). Importantly, the gratings presented to the two eyes had the same orientation within a given trial, with orientation randomized across trials.

2.3.2 Formal Experiment Binocular Rivalry Task

In the formal experiment, pre- and post-tests used a binocular rivalry task to measure changes in ocular dominance. Stimuli included two types of colored orthogonal sinusoidal gratings (Figure 1 [Figure 1: see original paper]A). One type consisted of a pair of circular red-green gratings (diameter: 1°, orientation: $±$45°, spatial frequency: 1 cpd, Michelson contrast: 80%, phase: 0 or π). The other type consisted of a pair of square yellow-blue gratings (diameter: 1°, orientation: $±$45°, spatial frequency: 3 cpd, Michelson contrast: 80%, phase: 0 or π). Because these test gratings differed in multiple basic features (color, shape, and spatial frequency), they likely activated relatively non-overlapping neural populations in early visual cortex.

Each trial lasted 60 seconds: 5 seconds of blank screen followed by 55 seconds of grating stimulation. In each trial, participants were presented with either red-green gratings (a) or yellow-blue gratings (b) to both eyes. Each binocular rivalry task consisted of 16 trials, with stimulus order balanced across trials according to a predetermined sequence (abbabaabbaababba or baababbaabbabaab), resulting in 8 trials for each grating type. To prevent visual aftereffects, phase values (0 or π) and orientations ($±$45°) remained constant within a trial but were randomized across trials. Critically, the same grating stimuli and presentation order were used in the post-test as in the corresponding pre-test.

2.3.3 Monocular Deprivation

For monocular deprivation, a translucent patch was used to cover the participant's dominant eye (i.e., the deprived eye, determined by pre-test binocular rivalry results). During the entire deprivation period, participants were required to keep the patched eye open, as recent research has found that keeping the patched eye open induces a larger deprivation effect than closing it (Chen et al., 2023).

2.3.4 Attention Tracking Task

The primary stimuli in the tracking task were colored gratings identical to those used in the pre- and post-test binocular rivalry tasks (Figure 1B). The display contained 10 red-green gratings and 10 yellow-blue gratings moving independently and smoothly in random directions within an 18°$×$18° gray square region. To create the appearance of rigid-body motion, gratings bounced off each other, the square boundaries, or the fixation point upon collision (He et al., 2021). Bounces occurred before actual contact, as if the gratings had a transparent shell with thickness equal to 10% of their diameter, which reduced visual crowding and task difficulty. The bounce angle followed physical collision principles, but speed remained constant. Additionally, frames from the TV series “iPartment” were processed into grayscale and displayed surrounding the square to enrich visual stimulation for the non-deprived eye.

The tracking task included two attention conditions: attend to red-green gratings and attend to yellow-blue gratings. At the beginning of each experimental session, instructions appeared at the center of the screen, cueing participants to allocate attention to either the red-green or yellow-blue gratings throughout the session while ignoring the other set. After 3 seconds, an 18°$×$18° gray square appeared containing 10 red-green and 10 yellow-blue gratings moving from random positions in random directions, with a grayscale image surrounding the square as background. All gratings were initially oriented horizontally or vertically. After 5–10 seconds, one red-green grating and one yellow-blue grating changed their orientation to 45° or –45°. One of these two gratings served as the target. For example, in the attend-red-green condition, the tilted red-green grating was defined as the target, and participants were required to continuously attend to and track its movement. After 20–25 seconds, both tilted gratings returned to their original orientations, and the instruction “Click the target ball” appeared above the square. Participants had 10 seconds to click the target grating’s current location as quickly and accurately as possible. Feedback was then displayed for 2 seconds. The attend-yellow-blue condition was identical except that the tilted yellow-blue grating served as the target.

Each tracking trial lasted 35–45 seconds, depending on reaction time. Participants could take a break of up to 20 seconds after every 30 trials. The total presentation time of colored gratings was controlled to be exactly 1 hour; if this duration was exceeded, the program automatically terminated after completing the current trial.

2.4 Procedure

Before the formal experiment, each participant underwent 3–6 days of practice with the binocular rivalry task. The purpose was to familiarize participants with the task and obtain stable ocular dominance measurements (Bao et al., 2018). Each practice day consisted of four blocks of binocular rivalry tasks. The first 5-minute block served as warm-up and was not included in data analysis. This was followed by three 16-minute blocks with 10-minute breaks between them. Participants were considered to have reached the practice criterion when their ocular dominance results across the last three tests varied by less than 10%, at which point they qualified for the formal experiment.

On each formal experiment day, participants first completed a 5-minute warm-up block of binocular rivalry tasks (using the same stimuli as in the practice phase), followed by a 5-minute break. They then performed two 16-minute pre-test blocks of binocular rivalry with a 10-minute break between them. Subsequently, participants completed the attention tracking task while undergoing monocular patching. Immediately after the tracking task, the eye patch was removed and participants completed a 16-minute post-test block of binocular rivalry. Each participant repeated the experiment twice in each attention condition, for a total of four formal experimental sessions conducted on different days.

Figure 1 shows the colored gratings used in the formal experiment's binocular rivalry task (A) and an example trial from the tracking task (B).

2.5 Data Analysis

To quantify ocular dominance from each binocular rivalry test, we calculated the total duration of exclusive and mixed percepts across all trials. We then computed an ocular dominance index (ODI) using the following formula:

$$\text{Ocular dominance index} = \frac{T_{\text{DE}}}{T_{\text{DE}} + T_{\text{NDE}}}$$

where T_{DE} represents the duration of perceiving stimuli presented to the deprived eye and T_{NDE} represents the duration of perceiving stimuli presented to the non-deprived eye. An ODI greater than 0.5 indicates that the deprived eye dominated in binocular rivalry. We used three-way repeated-measures ANOVA and Tukey's multiple comparisons test to compare ODI results between pre- and post-tests.

To examine whether attention modulates short-term monocular deprivation, we conducted a 2 (attention stimulus: red-green gratings, yellow-blue gratings) × 2 (test stimulus: red-green gratings, yellow-blue gratings) × 2 (test phase: pre-test, post-test) repeated-measures ANOVA on ODI results (Figure 2 [Figure 2: see original paper]A). Results revealed significant main effects of test stimulus ($F(1,19) = 26.97, p < .001, \eta^2 = 0.59$) and test phase ($F(1,19) = 18.89, p < .001, \eta^2 = 0.50$), with higher ODI in the post-test than pre-test, indicating enhanced dominance of the deprived eye after patching. Additionally, significant two-way interactions were found between attention stimulus and test stimulus ($F(1,19) = 6.34, p = .021, \eta^2 = 0.25$) and between test stimulus and test phase ($F(1,19) = 21.68, p < .001, \eta^2 = 0.53$). Most importantly, the three-way interaction among attention stimulus, test stimulus, and test phase was significant ($F(1,19) = 11.73, p = .003, \eta^2 = 0.38$).

To better understand this three-way interaction, we calculated "ODI change" by subtracting pre-test ODI from post-test ODI (Figure 2B), allowing us to compare the magnitude of short-term monocular deprivation effects across attention conditions and test stimuli. The interaction between attention stimulus and test stimulus on ODI change was significant, consistent with the three-way interaction result. Given the limited comparability of binocular rivalry performance measured with different test stimuli, we focused on comparing ODI change for the same test stimulus across different attention conditions. When test stimuli were yellow-blue gratings, ODI change was significantly greater in the attend-yellow-blue condition ($M = 0.023, SE = 0.006$) than in the attend-red-green condition ($M = 0.006, SE = 0.007, t(19) = -2.51, p = .021, d = -0.56, 95\% CI = [-1.027, -0.082]$, FDR-corrected $p = .042$). When test stimuli were red-green gratings, a similar trend was observed but did not reach significance (attend-red-green: $M = 0.081, SE = 0.018$; attend-yellow-blue: $M = 0.057, SE = 0.016$; $t(19) = 1.549, p = .138, d = 0.346, 95\% CI = [-0.110, 0.794]$). These results indicate that short-term monocular deprivation effects are larger when test stimuli share features with target stimuli in the tracking task and relatively smaller when they share features with distractor stimuli, with this effect being more robust for yellow-blue test gratings.

Figure 2 shows pre- and post-test ODI results across attention conditions and test stimuli (A), and ODI change across conditions (B). Bar graphs represent group means, gray lines show individual participant data, and error bars represent standard errors of the mean.

Discussion

The present study aimed to explore whether attention can modulate short-term monocular deprivation effects in adults. Our results generally support an affirmative answer to this question. Specifically, we found that when ocular dominance was tested with yellow-blue gratings, the monocular deprivation effect was significantly larger if participants attended to yellow-blue gratings during deprivation compared to when they attended to red-green gratings. When tested with red-green gratings, we observed a similar but non-significant trend.

This finding contradicts the null results reported in a previous study (Chen et al., 2020). In that study, attentional engagement varied across different deprivation sessions, which may have introduced between-session variability that obscured differences in deprivation effects across attentional conditions. In their most attentionally demanding condition, participants played an action video game, a highly attention-consuming activity (Bavelier & Green, 2019). In their less demanding conditions, participants played non-action games or watched silent replays of action games. However, they did not objectively measure attentional engagement in each condition. The attentional level in the silent replay condition is questionable, as participants might have allocated more attention than anticipated. Indeed, people may sometimes deploy more visual attention when watching silent films compared to films with sound (Song, Lyu, Zhao, et al., 2023). Another potential factor contributing to their null result was the use of a binocular phase combination task to measure ocular dominance, which primarily probes activity of simple cells in V1 visual cortex (Huang et al., 2010). In contrast, our binocular rivalry task likely involves a broader population of neural processing (Bai et al., 2017), some of which may be more sensitive to attentional modulation (Tootell et al., 1998).

An unexpected finding in our study was that the deprivation effect measured with red-green gratings was significantly larger than that measured with yellow-blue gratings. This phenomenon is not easily explained, as previous studies in this field typically used red-green or red-blue gratings rather than yellow-blue gratings in binocular rivalry tasks (Animali et al., 2023; Binda et al., 2018; Kurzawski et al., 2022; Lunghi et al., 2013; Lunghi, Emir, et al., 2015; Nguyen et al., 2021; Virathone et al., 2021; Zhou et al., 2017). It is known that the parvocellular (P) pathway is highly sensitive to red-green contrast, while the koniocellular (K) pathway is specialized for yellow-blue discrimination (Anssari et al., 2020). Previous animal studies and human monocular deprivation research suggest that the P pathway is more sensitive to visual deprivation (Binda et al., 2018; Horton & Hocking, 1997). We therefore speculate that short-term monocular deprivation may have stronger effects on the P pathway than the K pathway. This strong P pathway effect might have created a ceiling effect when we measured ocular dominance with red-green gratings, making it difficult to observe significant attentional modulation in this test condition.

In summary, the present study provides preliminary evidence supporting a modulatory role of attention in typical monocular deprivation effects. Our findings suggest that short-term ocular dominance plasticity is not solely determined by imbalanced visual feedforward input but is also influenced by top-down attentional feedback, revealing potential interactions between higher-level cognitive functions and lower-level visual processing in this phenomenon. Given that monocular deprivation paradigms have recently been used to treat amblyopia (Lunghi et al., 2019; Zhou et al., 2019), our discovery of attentional modulation on this effect may offer clinical insights for optimizing such treatments in the future.

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Note: Figure translations are in progress. See original paper for figures.