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The Best of Both Worlds: Adaptation During Natural Tasks Produces Long-Lasting Plasticity in Perceptual Ocular Dominance

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Abstract

In human vision, one eye is usually stronger than the other. This is called *ocular dominance*. Extremely imbalanced ocular dominance can be found among certain patient groups, for example, in patients with amblyopia. Here, we introduce a novel method to rebalance ocular dominance. We developed an altered-reality system that subjects used to interact with the natural world, the appearance of which was changed through a real-time image process. Several daily adaptation sessions lasting 3 hr each reduced sensory ocular dominance in adults who were not diagnosed with amblyopia and improved vision in patients with amblyopia. Surprising additional strengthening was found over the subsequent 2 months, when subjects experienced natural vision only. Our method effectively trains subjects to use both eyes in the wide variety of everyday tasks. The transfer of this training to everyday vision likely produced the continuing growth in effects during the months after the training. These findings are promising for the application of this method in future clinical research on amblyopia.

Keywords

ocular dominance, plasticity, adaptation, patchwork, binocular rivalry

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Functional asymmetries of the two eyes, now termed *ocular dominance*, were described as early as 330 BC, by Aristotle. Abnormal visual experience can severely change neural and perceptual ocular dominance in juveniles, but not necessarily in adults. For example, occluding kittens' vision through one eye causes cortical blindness for that eye, but monocular deprivation in adult cats produces no detectable abnormalities (Wiesel & Hubel, 1963). This greater malleability of ocular dominance in juveniles compared with adults is well documented (Holmes et al., 2011; Hubel & Wiesel, 1970).

Recent studies, however, have found that adults' ocular dominance may be more plastic than previously believed, opening a window of opportunity for treating adults with amblyopia (He, Ray, Dennis, & Quinlan, 2007; Sale et al., 2007). In rodents, a number of neurochemical and behavioral interventions have been shown to rejuvenate visual cortex, allowing the reinstatement of plasticity in ocular dominance (e.g., Greifzu et al., 2014; Maya Vetencourt et al., 2008). Human subjects are able to perform everyday activities during adaptation to changes in visual input, such as when they wear an eye patch (Lunghi, Burr, & Morrone, 2011). However, past adaptation-based methods have produced relatively short-lasting effects (Lunghi, Burr, & Morrone, 2013).

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Another approach has been to train subjects with amblyopia in behavioral tasks aimed at strengthening cortical representations of the input to the weak (amblyopic) eye. These tasks generally reduce input to the strong (fellow) eye, either completely, so that the weak eye receives monocular training (Levi & Polat, 1996; Polat, Ma-Naim, Belkin, & Sagi, 2004), or partially, so that training is binocular and signals from the two eyes are more balanced (Hess & Thompson, 2015; J. Li et al., 2013; S. L. Li et al., 2015; Vedamurthy et al., 2015). Almost all of this work has relied on training with specific tasks in the laboratory. However, frequent training sessions can be difficult to integrate into patients' life and work, which limits compliance. In addition, perceptual learning of this type can become overtrained with continued practice, which limits transfer of perceptual gains to general vision outside the task (Sagi, 2011).

In the work we report here, we aimed to overcome these limitations. Our approach was to manipulate the visual world electronically in order to incorporate training into everyday life. The rise of wearable video technology, such as Google Glass and Hololens, promises technological and social advances that will make such real-world interventions even more appealing in the near future.

We used an altered-reality system to balance sensory ocular dominance of adults while they performed everyday activities. Subjects viewed the world through this system, which comprised a head-mounted video camera that fed into an image-processing computer that in turn drove a head-mounted display (HMD). Video images in each eye were divided into a number of square cells (see Fig. 1). In half of the cells, the color was replaced by the mean color of all the pixels within that cell; the original content of the remaining cells was unaltered. The location of the altered cells was randomized and dynamically updated. The images presented to the two eyes were complementary, such that each uniform cell presented to one eye corresponded to an intact image patch presented to the other, and vice versa. Viewing this complementary-patchwork video, subjects were able to interact with the world but were required to integrate the visual inputs from both eyes in order to see a complete image. Furthermore, perceiving an image with relatively equal clarity across the patches required equal weighting of the inputs from the two eyes. We expected that adapting to these complementary patchworks would cause the visual system to move toward balancing the two eyes' inputs. In two experiments, we first tested this system in adults who had not been diagnosed with amblyopia, but who possessed relatively large sensory ocular dominance. We then tested the system in patients with amblyopia.

In Experiment 1, we assessed sensory ocular dominance before and following adaptation to the altered reality by using a test of binocular rivalry, a phenomenon traditionally ascribed to interocular interactions in early visual cortex (Blake, 1989). In binocular rivalry, dissimilar images are presented to the two eyes, and subjects perceive the two images in alternation, rather than a combined image. Typically, the image presented to a subject's stronger eye is perceived a greater proportion of the time than the image presented to the subject's weaker eye. In this article, *predominance* for a given percept refers to the proportion of the time that a subject reported seeing that percept. We found that exposure to the patchwork input led to predominance becoming more equal between the inputs to the two eyes. In Experiment 2, we then tested subjects with six other visual tasks to determine whether this adaptation training would reshape visual functioning in these tasks. Finally, in Experiment 3, we tested whether our method would improve the vision of patients with amblyopia.

Method

Our experimental procedures were approved by the institutional review board of the Institute of Psychology, Chinese Academy of Sciences, and informed consent was obtained from all subjects. Before we conducted the experiments, the numbers of subjects were predetermined on the basis of the sample sizes for previous studies in this field.

Hardware

We developed two altered-reality systems for this study. Each comprised a camera (The Imaging Source Asia Co., Ltd., Taipei City, Taiwan) connected to a computer that fed into an HMD. One system used a DFK-22AUC03 USB 2.0 camera (640- × 480-pixel RGB24 video recorded at 60 Hz) connected to a Dell Optiplex 9010MT computer with an Nvidia (Santa Clara, CA) GeForce GTX670 graphics processing unit. The other system used a DFK-23UM021 USB 3.0 camera (1,280- × 720-pixel RGB32 video recorded at 30 Hz) connected to a Dell XPS 8700 computer with an Nvidia GeForce GTX770 graphics processing unit. The HMDs were Sony HMZ-T2 (organic-light-emitting-diode display, 49.4° in horizontal, 27.8° in vertical, resolution = 1,280 × 720 pixels).

Image acquisition and image processing

Custom software controlled the image processing; MATLAB (The MathWorks, Natick, MA), a TISImaq plug-in

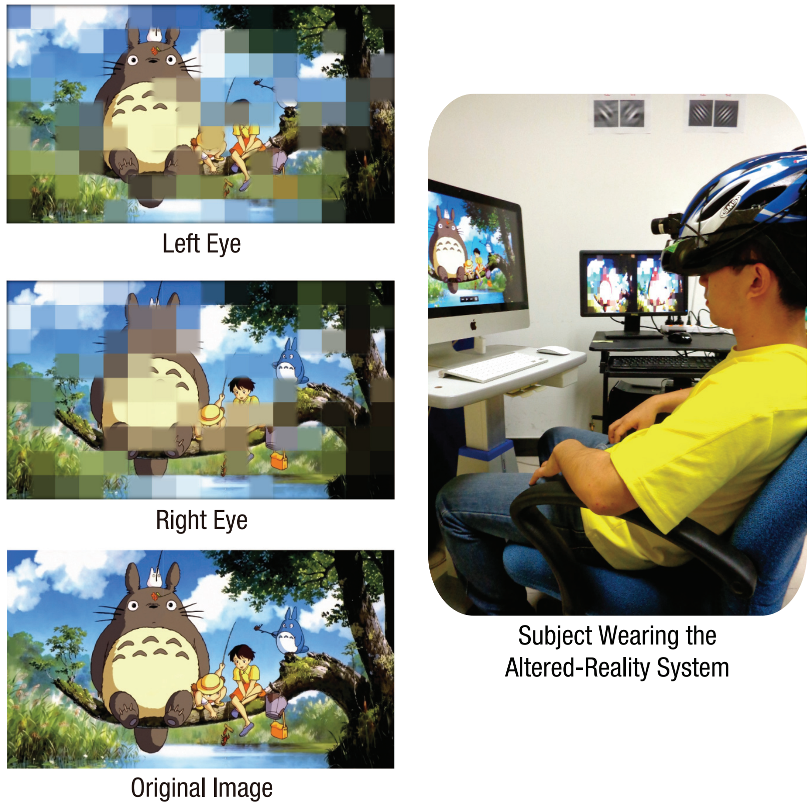

Fig. 1. Illustration of the altered-reality system. As shown on the right, subjects wore a head-mounted display and a video camera. The camera streamed video of what subjects were looking toward to a computer that rendered the originally captured images as patchworks, which were then input to the head-mounted display; the patchworks of the video images presented to the two eyes were complementary to each other. In the example shown on the left, the portion of the original image centered on the character Totoro's face is rendered differentially in the images presented to the two eyes: Totoro's face is visible in the image presented to the left eye but is replaced with square cells of uniform color in the image presented to the right eye. With this altered-reality system, subjects had to make use of the visual inputs to the two eyes cooperatively in order to see an intact world. Note that the example images shown here are for demonstration purposes only. In the experiment, the video images included the ambient world captured by the camera in real time.

(supported by The Imaging Source), and Psychophysics toolboxes (Brainard, 1997) were used to acquire, process, and display the stimuli. For the DFK-22AUC03 system but not the DFK-23UM021 system, the camera images were clipped to a resolution of 640 × 360 pixels and then expanded to a resolution of 1,280 × 720 pixels. During adaptation, the video images presented to each eye were divided into a 9 × 16 grid of square cells (3.1° each). The color in half of the cells was altered such that each was rendered uniformly in the mean color of all the pixels within that cell; the content of the remaining cells was unaltered. The location of the uniform cells was randomized and updated every 10 to 50 s (30 s on average). The images presented to the two eyes were complementary, such that uniform cells presented to one eye corresponded to intact image patches presented to the other (see Fig. 1).

Experiment 1: binocular rivalry before and after five daily adaptation sessions

Subjects. Ten naive observers (6 females, 4 males; age range = 18–28 years) participated in Experiment 1. They were selected from a total sample of 25 adults on the basis of their eye dominance during binocular rivalry. We calculated each potential subject's interocular-imbalance index as follows: $(P_{strong} + P_{mixed}/2)/(P_{weak} + P_{mixed}/2)$, where P_{strong}, P_{weak}, and P_{mixed} represented the predominance for the input to the stronger eye, the input to the weaker eye, and mixed percepts (fusion or piecemeal), respectively. Only subjects whose interocular-imbalance indices exceeded 1.2 were recruited for this experiment because we did not expect sensory ocular dominance in people with very balanced eyes to be changed very much by our altered-reality technique.

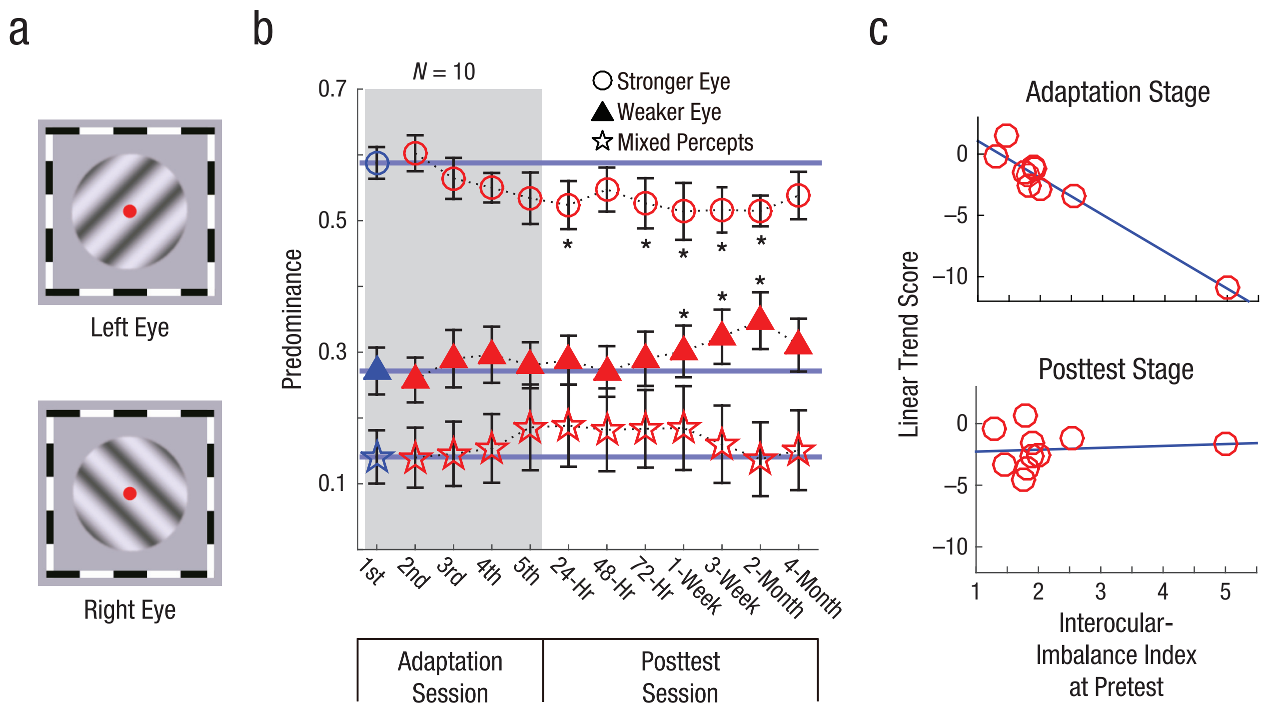

Fig. 2. Experiment 1: illustration of the stimuli and results. This experiment used a binocular-rivalry task (a), in which orthogonally oriented grating stimuli were presented to the right and left eyes. The graph in (b) shows grand-average predominance of the input to the stronger eye, the input to the weaker eye, and mixed percepts as a function of session. Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the baseline value in the pretest ($p < .05$). The graphs in (c) show the relationship between interocular imbalance in the pretest and linear trend score, separately for the adaptation and posttest sessions. Each circle represents a single subject. The blue line shows the linear fit to the data of all the subjects. More negative linear-trend scores indicate more profound interocular rebalancing.

Before adaptation, the predominance for the input to the stronger eye was, on average, 58.8% for these 10 observers (*SD* = 7.6%, range = 48.2%–70.1%). Because the results of our pilot experiment, which used the same screening procedure, suggested that daily sessions in which the original, unaltered images were presented through the HMD did not affect ocular dominance (see Supplemental Experiment 1, in the Supplemental Material available online), we tracked only the effects of adaptation to complementary patchworks in this experiment (i.e., we did not include a control condition in which the video was unaltered).

Stimuli. The rival stimuli were two dichoptically presented circular patches of sine-wave gratings (3 cycles/deg, 80% Michaelson contrast) with orthogonal orientations (±45° from vertical); their edges had been smoothed with a Gaussian filter (see Fig. 2a). The patches subtended 1° and were displayed foveally, each surrounded by a high-contrast 2.5° × 2.5° checkerboard frame (0.25° thick) that promoted stable binocular alignment. There was also a small red central fixation point (0.08° in diameter) presented to both eyes.

Task and procedure. This experiment involved three stages: practice, adaptation, and posttest. Binocular-rivalry tests were conducted in all three stages. In the practice and posttest stages, subjects performed only binocular-rivalry tests. The adaptation stage included both binocular-rivalry tests and adaptation sessions.

Practice. During the practice stage, we asked all subjects to complete four binocular-rivalry tests per day for 7 continuous days, to ensure that they were familiar with the task and their performance became stable.

Adaptation. On each of the 5 days of the adaptation stage, subjects completed four binocular-rivalry tests before a 3-hr session in which they adapted to the complementary-patchwork video. The four binocular-rivalry tests before the first adaptation session constituted the pretest. The binocular-rivalry tests before each subsequent adaptation session were used to track the change of perceptual ocular dominance relative to the pretest over the 5 days of adaptation training. Our pilot experiment and the subjects' practice data indicated that binocular rivalry was more variable in the first test of a day than in the subsequent tests. Therefore, in Experiment 1, we considered the first test on each adaptation day to be practice.

During adaptation, subjects could view the environment in front of them through the altered-reality system, and they could perform everyday activities within the laboratory room, such as watching movies, playing video games, eating, and walking. Subjects were told to sleep well after completing the session on each adaptation day.

Posttest. Follow-up sessions took place 24 hr, 2 days, 3 days, 1 week, 3 weeks, 2 months, and 4 months after the last adaptation session. On each posttest day, subjects completed four binocular-rivalry tests; the first test was considered to be practice. The binocular-rivalry tests in this stage tracked the change in perceptual ocular dominance after adaptation training ended.

Binocular-rivalry tests. All binocular-rivalry tests were conducted using the HMDs. Each test consisted of 10 trials, lasted for 10 min, and was followed by a 10-min break during which subjects removed the HMD and viewed the world normally. Including these rest periods likely avoided the increase in piecemeal percepts that comes with prolonged exposure to binocular rivalry (Klink, Brascamp, Blake, & van Wezel, 2010). At the start of each test, the alignment of the subject's eyes was verified using a modified nonius fixation cue, a dichoptically presented annulus. Subjects pressed the up-arrow key when they could see a normal intact annulus, which was an indication of good alignment of the eyes. That key press led to the removal of the nonius cue and the presentation of the rival stimuli. Each trial lasted for 1 min; the rival gratings were presented for 55 s and were followed by a 5-s blank interval. The orientations of the gratings were kept constant within a trial. However, the eye to which the clockwise-tilted grating was presented (and consequently, the eye to which the counterclockwise-tilted grating was presented) changed randomly across trials. Subjects reported their perception (a grating tilted counterclockwise from vertical, a grating tilted clockwise from vertical, or a piecemeal perception, usually a mixed percept that combined the two grating patches—see Fig. S1a in the Supplemental Material for examples) by pressing and holding one of three keys (left-, right-, or down-arrow) on the keyboard.

Data analysis. Phase durations of exclusively monocular percepts and piecemeal (mixed) percepts were summed up across all the trials of a test to calculate predominance for the input to the left eye, the input to the right eye, and piecemeal percepts. Predominance values from the last three binocular-rivalry tests in the pretest session were averaged to estimate the baseline. Similarly, predominance values from the last three tests on each subsequent adaptation and follow-up day were used to track training effects.

Linear trend analyses were performed on both the predominance of different percepts and the interocular-imbalance index to estimate how the effects of interocular rebalancing developed during the 5 days of adaptation and the follow-up testing. Specifically, the interocular-imbalance indices before the five adaptation sessions were multiplied with a contrast vector of [−4 −2 0 2 4], and the interocular-imbalance indices before the seven follow-up sessions were multiplied with a contrast vector of [−6 −4 −2 0 2 4 6]. For each of the two stages, the sum of the product was defined as the linear trend score. More negative trend scores indicated a greater decrease in interocular imbalance over time, therefore suggesting stronger linear rebalancing.

Experiment 2: performance on other visual tasks before and after five daily adaptation sessions

Subjects. Twenty-five naive observers participated in Experiment 2 (17 females, 8 males; age range = 20–26 years). They were screened for interocular imbalance as in Experiment 1. All subjects had normal or corrected-to-normal vision. We collected data from 9 subjects for each of six visual tasks other than binocular-rivalry tasks. Detailed information on the assignment of subjects to tasks can be found in the Supplemental Material.

To examine whether the training effects we observed resulted from general perceptual learning due to repeated testing, we also tested 10 subjects on the same six visual tasks before and after 5 days of living in the normal visual environment. Nine of these subjects had never participated in the adaptation training.

General procedure. We assessed subjects' performance on tests of dichoptic motion coherence (to test the signal-to-noise ratio for motion processing in each eye; Experiment 2a), visual acuity (Experiment 2b), the Ebbinghaus illusion (to test spatial contextual effects likely linked to inhibitory mechanisms; Experiment 2c), interocular phase combination (to test sensory ocular dominance in binocular integration, or fusion; Experiment 2d), interocular grouping (Experiment 2e), and stereo sensitivity (Experiment 2f). We included a test of interocular phase combination to complement our previous assessment of how our adaptation method affects sensory ocular dominance involving direct interocular competition (i.e., binocular rivalry).

The pretest for each task was conducted in a separate session on the day before the first adaptation session. The adaptation procedure was the same as in

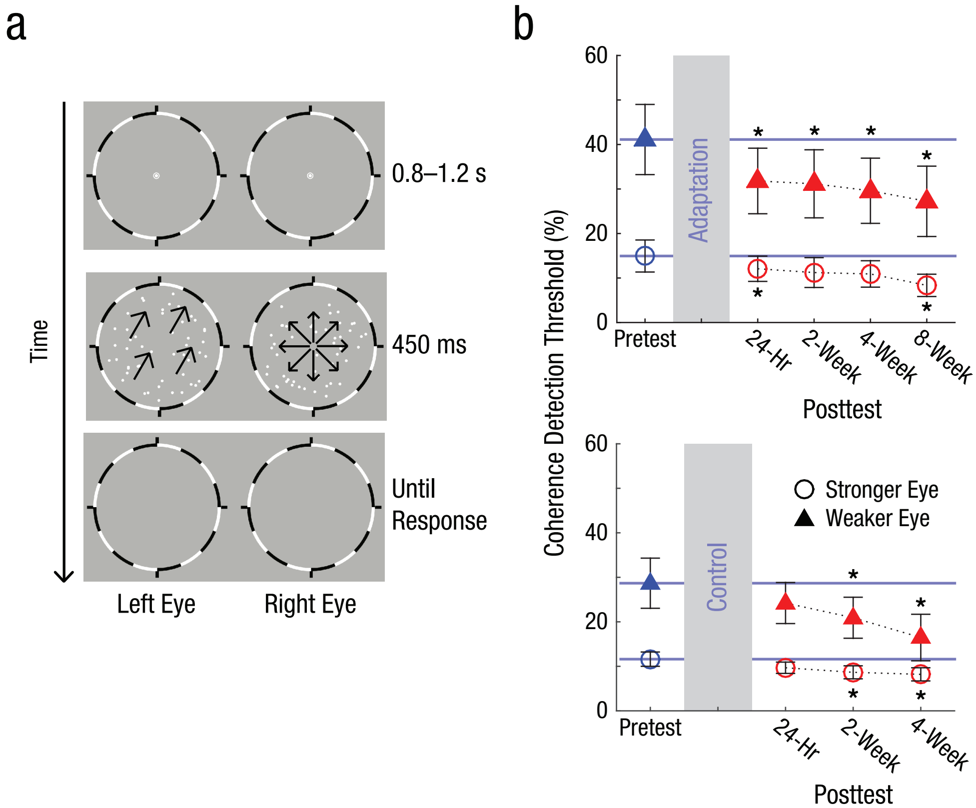

Fig. 3. Experiment 2a (dichoptic motion coherence): illustration of the task and results. On each trial (a), an array of moving dots within a circular window was presented to each eye. Their initial positions within the window were randomly assigned. The dots presented to one eye all moved in the same direction, whereas the dots presented to the other eye moved in random directions. The dots all moved at a constant speed (5.9°/s) and wrapped around to the opposite side of the window when they reached the perimeter. Subjects indicated whether the direction of coherent motion was tilted clockwise or counterclockwise from vertical. The graphs in (b) show grand-average coherence-detection thresholds for the stronger eye and the weaker eye at the pretest and each of the posttests, separately for the adaptation group (top) and the control group (bottom). Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$).

Experiment 1. However, there were no tests before each adaptation session. Posttests were performed 24 hr, 2 weeks (for four of the tasks; see the Supplemental Material), 4 weeks, and 8 weeks after the last adaptation session.

Figures 3a, 4a, 5a, 6a, 7a, and 8a illustrate the stimuli and trial sequences for the six tasks. Additional methodological details are provided in the Supplemental Material.

Experiment 3: visual improvement after adaptation training in patients with amblyopia

Subjects. Eighteen patients with amblyopia (6 males, 12 females; age range = 14–35 years) were recruited. All were naive to the rationale of the adaptation and testing methods. Four of the patients had both anisometropia and strabismus, 1 had both anisometropia and cataracts, and the others had anisometropia only. In addition, 2 of the subjects had bilateral amblyopia, and all the others had unilateral amblyopia. Table 1 lists the patients' clinical details.

Before participating in Experiment 3, 3 of the patients had participated in a pilot experiment with the same procedure as in Experiment 3 except that visual acuity was also measured before each daily adaptation session. These 3 patients completed the pilot experiment 1 week to 2 months before Experiment 3 and had no adaptation training during that intervening period. The visual-acuity data for these patients is reported in Table S2 in the Supplemental Material. To avoid potential practice effects, we did not administer any tests during the adaptation stage in the formal experiment.

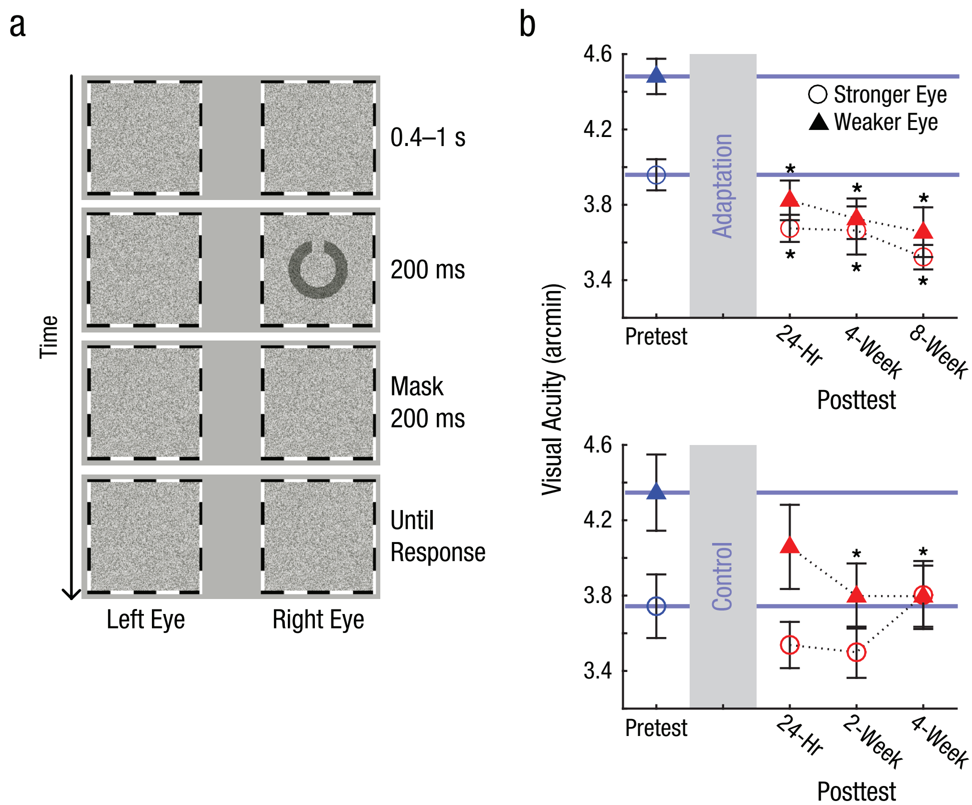

Fig. 4. Experiment 2b (visual acuity): illustration of the task and results. Each trial (a) started with presentation of a white-noise image to each eye. After 0.4 to 1 s, a Landolt C, randomly oriented with the gap in one of the four cardinal positions, was embedded in the white noise presented to one eye. Subjects pressed one of the arrow keys to indicate the orientation of the Landolt C (up, down, left, or right; four-alternative forced-choice task). The graphs in (b) show grand-average visual acuity for the stronger eye and the weaker eye at the pretest and each of the posttests, separately for the adaptation group (top) and the control group (bottom). Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$).

Procedure. The adaptation procedure was the same as in Experiments 1 and 2 except for two changes. First, the video contrast in the fellow eye was lowered to a certain degree based on a measurement of dichoptic contrast matching (see the Supplemental Material) before each adaptation session. Second, the patients adapted to the patchwork images during seven, rather than five, daily 3-hr sessions. The first manipulation was intended to encourage the patients to use both eyes.

Visual acuity (see Fig. 9b), stereo acuity, and contrast sensitivity were measured before and after the adaptation training (see the Supplemental Material for details). The posttests were performed 24 hr, 1 week, and 4 weeks after the end of the training. Visual acuity was measured with the FrACT (Bach, 1996). The Titmus Stereo Test (Stereo Optical Co., Inc., Chicago, IL) was used to measure stereo acuity. Contrast sensitivity for varied spatial frequencies (0.5–16 cycles/deg) was measured in a two-interval forced-choice detection task using a 3-down/1-up staircase procedure. More details can be found in the Supplemental Material.

Results

Experiment 1

Repeated adaptation to the patchwork images progressively increased the subjects' interocular balance (see Fig. 2b). A linear trend analysis across the 5 days revealed a decreasing trend for the predominance of the input to the stronger eye, $t(9) = 2.75$, $p = .022$, Cohen's d (hereafter, simply d) = 0.87, 95% confidence interval (CI) = [−0.58, −0.06] (the reported CIs are the CIs for the difference between population means in the case of paired-samples t tests and for the population mean in the case of one-sample t test), though we did not find a significant increasing trend for the predominance of the input to the weaker eye, $t(9) = 1.78$, $p = .109$, $d = 0.56$, CI = [−0.03,

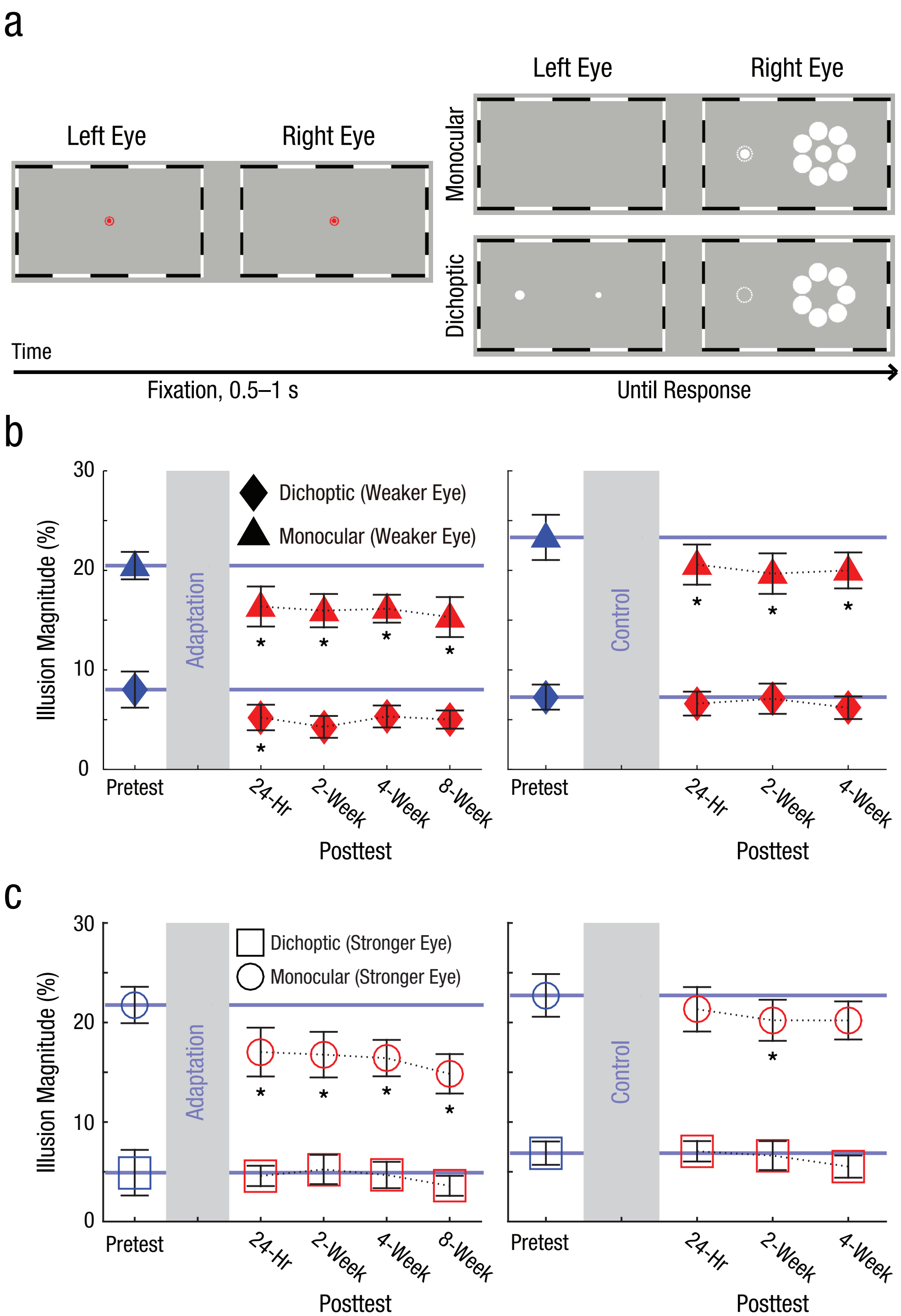

Fig. 5. Experiment 2c (Ebbinghaus illusion): illustration of the task and results. Each trial (a) began with presentation of a red fixation dot to each eye. Next, a reference circle of fixed size and a test circle of adjustable size were presented to one eye. Subjects' task was to adjust the size of the test circle (via key presses) to match the size of the reference circle. On monocular trials, the test circle was surrounded by a ring of 7 large circles, and the reference circle was surrounded by a ring of 19 small circles (a blank screen was presented to the opposite eye). On dichoptic trials, these inducers were presented to one eye, and the test and reference circles were presented to the opposite eye. The graphs show the grand-average magnitude of the illusion for the (b) weaker eye and (c) stronger eye at the pretest and each of the posttests, separately for the dichoptic and monocular conditions, for the adaptation group (left) and the control group (right). The magnitude of the illusion was calculated as follows: (size of test circle – size of reference circle)/size of reference circle. Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$).

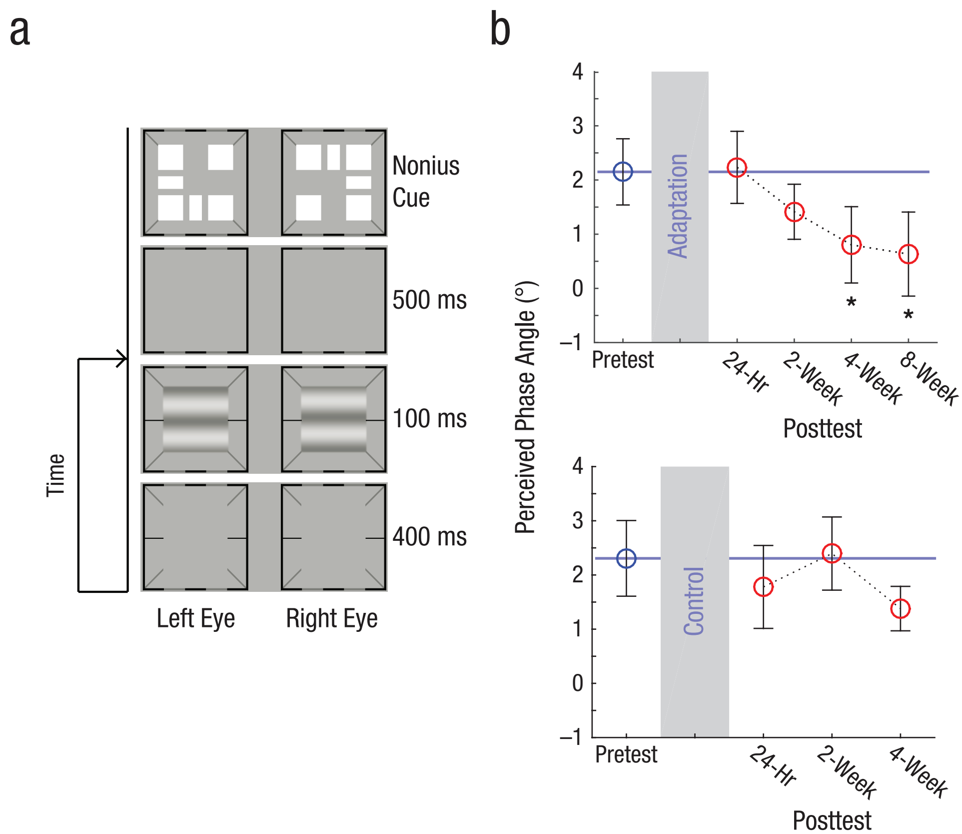

Fig. 6. Experiment 2d (interocular phase combination): illustration of the task and results. Before starting each trial (a), subjects had to ensure that they could see an intact nonius cue. Then, test sinusoidal gratings (displayed for 100 ms) and a 400-ms blank interval were presented in alternation. Each grating contained 2 cycles; the spatial phase of one grating (here, the grating on the right) was shifted 22.5° (i.e., 1/16 cycle) above the horizontal midline of the patch, and the spatial phase of the other grating (here, the grating on the left) was shifted 22.5° below the horizontal midline of the patch. In binocular integration, when different images (e.g., the two gratings here) are displayed on the two retinas, only a single combined *cyclopean* image is perceived. The perceived phase angle of the cyclopean grating is a certain value between the phase angles of the two stimulus gratings. Subjects' task was to adjust the vertical position of a 1-pixel horizontal reference line to indicate the center of the perceived cyclopean grating, using the up- and down-arrow keys. The graphs in (b) show the grand-average perceived phase angle at the pretest and each of the posttests, separately for the adaptation group (top) and the control group (bottom). Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$).

0.25], or for the predominance of mixed percepts, $t(9) = 1.49$, $p = .170$, $d = 0.47$, CI = [−0.11, 0.52]. Note that predominance in binocular rivalry shows only the *relative* strengths of the signals from the two eyes. Thus, either reduced predominance of the input to the stronger eye or increased predominance of the input to the weaker eye can be an indication of increased interocular balance.

After the 5-day adaptation stage ended, the subjects' interocular balance continued to improve over 2 months of living in the normal visual environment, although there was a slight decay after 4 months. In case the trend of interocular rebalancing was due to a coincidence, we included the 4-month posttest in the trend analysis (the trend analysis without this posttest also showed significant results). The interocular-imbalance index showed a decreasing trend across the seven posttest sessions (24 hr–4 months), $t(9) = 3.04$, $p = .014$, $d = 0.96$, 95% CI = [−3.30, −0.48]. Specifically, there was an increasing trend for the predominance of the input to the weaker eye, $t(9) = 3.33$, $p = .009$, $d = 1.05$, 95% CI = [0.16, 0.86], and a decreasing trend for the predominance of mixed percepts, $t(9) = 2.65$, $p = .027$, $d = 0.84$, 95% CI = [−0.83, −0.07], but no significant change for the predominance of the input to the stronger eye, $t(9) = 0.75$, $p > .250$. Even after 4 months, the interocular-imbalance index remained significantly smaller than at baseline, $t(9) = 2.68$, $p = .025$, $d = 0.85$,

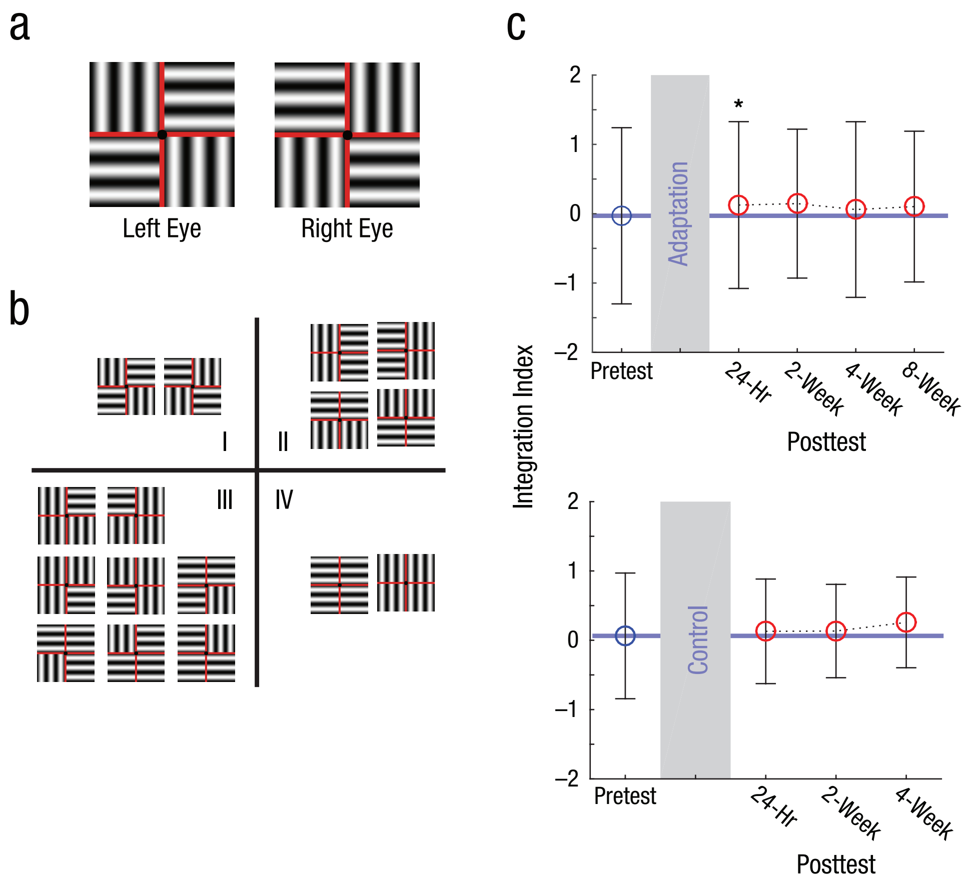

Fig. 7. Experiment 2e (interocular grouping): illustration of the task and results. On each trial (a), a 2 × 2 checkerboard of horizontal and vertical grating patches was presented to each eye. Corresponding patches on the two checkerboards were perpendicular to each other, which produced binocular rivalry. Such stimuli can generate percepts (b) that vary in the extent of interocular grouping: complete grouping (i.e., all horizontal or all vertical gratings; type IV), partial grouping (types II and III), and no grouping (i.e., either monocular pattern; type I). Subjects reported which of these four categories the stimulus they perceived belonged to by pressing and holding down one of the four arrow keys on the keyboard. The graphs in (c) show the grand-average integration index at the pretest and each of the posttests, separately for the adaptation group (top) and the control group (bottom). The integration index was calculated from the weighted predominance for each of the four types of percepts; larger positive values correspond to stronger interocular grouping (see the Supplemental Material for more details). Error bars represent ±1 *SEM*. The asterisk indicates a significant difference from the pretest ($p < .05$).

95% CI = [−0.81, −0.07]. (See also the Supplemental Material for results of analyses of the distribution of phase durations and switching rates.)

Experiment 2

Table 2 compares the effect sizes observed for the adaptation and control groups in all the tests in Experiment 2 (see Tables S3 and S4 in the Supplemental Material for the specific p and d values).

Dichoptic motion coherence (Experiment 2a). The adaptation training reduced the coherence detection threshold for the weaker eye (see Fig. 3b). Specifically, this threshold decreased from 41.1% to 31.8% at the 24-hr posttest, $t(8) = 3.33$, $p = .010$, $d = 1.11$, 95% CI = [−15.76, −2.87]. Thereafter, the threshold further decreased—to 31.2% after 2 weeks, $t(8) = 4.55$, $p = .002$, $d = 1.52$, 95% CI = [−14.99, −4.91]); to 29.6% after 4 weeks, $t(8) = 3.20$, $p = .013$, $d = 1.06$, 95% CI = [−19.82, −3.20]); and to 27.2% after 8 weeks, $t(8) = 3.67$, $p = .006$, $d = 1.22$, 95% CI = [−22.61, −5.17]. Adaptation training also slightly reduced the coherence-detection threshold for the stronger eye (ps < .05 for the 24-hr and 8-week posttests; Fig. 3b).

To examine whether there was any general learning due to testing, we measured coherence-detection

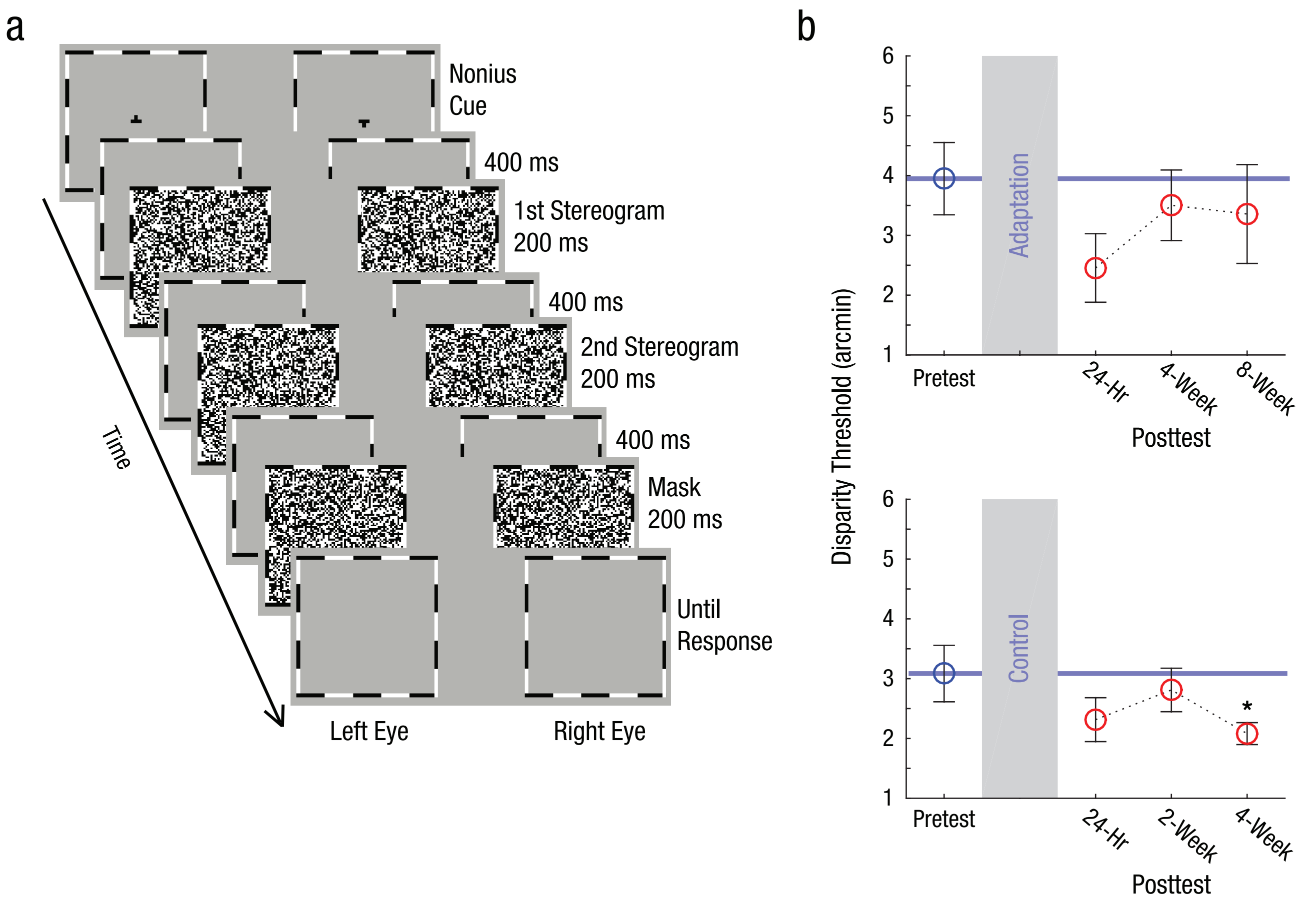

Fig. 8. Experiment 2f (stereo sensitivity): illustration of the task and results. Following presentation of nonius stimuli to verify binocular fusion, a crossed-disparity disc, which appeared nearer to subjects than the fixation plane, was randomly displayed in one of two stereogram intervals that alternated with blank displays and were followed by a mask (a). Subjects' task was to indicate whether the disc appeared in the first or second stereogram. The graph in (b) shows the grand-average detection threshold at the pretest and each of the posttests, separately for the adaptation group (top) and the control group (bottom). Error bars represent ±1 *SEM*. The asterisk indicates a significant difference from the pretest ($p < .05$).

thresholds before and after 5 days of living in the normal visual environment in the control group. Although we observed reduced thresholds in the 2-week and 4-week posttests (see Fig. 3b), as shown in Table 2, the effect sizes for the weaker eye were smaller in the control group than in the adaptation group (except for the 4-week posttest). These results suggest that there might be a weak learning effect for repeated testing of dichoptic motion coherence. However, this general learning effect was not strong enough to account for the effects observed in the adaptation group. Thus, we conclude that repeated adaptation to the patchwork images over five daily sessions increased the signal-to-noise ratio for the weaker eye.

Visual acuity (Experiment 2b). Visual acuity improved immediately after training (24-hr posttest) in both the stronger eye, $t(8) = 3.50$, $p = .008$, $d = 1.17$, 95% CI = [−0.47, −0.10], and the weaker eye, $t(8) = 8.62$, $p < .001$, $d = 2.87$, 95% CI = [−0.83, −0.48] (see Fig. 4b). The improvements remained significant for at least 8 weeks—4-week posttest: $t(8) = 3.07$, $p = .015$, $d = 1.02$, 95% CI = [−0.52, −0.07], for the stronger eye and $t(8) = 17.33$, $p < .001$, $d = 5.78$, 95% CI = [−0.86, −0.66], for the weaker eye; 8-week posttest: $t(8) = 4.56$, $p = .002$, $d = 1.52$, 95% CI = [−0.66, −0.22], for the stronger eye and $t(8) = 11.22$, $p < .001$, $d = 3.74$, 95% CI = [−1.00, −0.66], for the weaker eye.

The control group showed similar improvements of visual acuity for the weaker eye at the 2-week posttest, $t(9) = 4.63$, $p = .001$, $d = 1.46$, 95% CI = [−0.82, −0.28], and the 4-week posttest, $t(9) = 5.00$, $p < .001$, $d = 1.58$, 95% CI = [−0.80, −0.30] (see Fig. 4b). As shown in Table 2, however, these effects were smaller than the effects observed in the adaptation group, which suggests that a general learning effect cannot account for the adaptation group's improvements.

Table 1. Clinical Details of the Patients in Experiment 3

Patient	Age (years)	Gender	Left eye: Acuity[a] (logMAR)	Left eye: Refraction	Right eye: Acuity[a] (logMAR)	Right eye: Refraction	Type of amblyopia	Stereo acuity[b] (arcseconds)
01	22	Male	–0.3	–3.0	0.16	+5.50/–1.5×147	Anisometropia (right eye)	> 400
02	35	Female	–0.12	+1.75/–0.50×82	0.21	+5.25/–0.75×161	Anisometropia (right eye)	100
03	20	Male	0.65	+7.25/+0.75×155	–0.32	+1.25	Anisometropia (left eye)	50
04	23	Male	–0.16	–6.00/–0.25×152	0.82	–8.25/–1.50×33	Anisometropia (right eye)	400
05	14	Male	0.2	+0.75	0.46	+3.50/+0.75×85	Anisometropia (right eye)	0
06	24	Female	1.64	+4.50/+3.50×125	–0.11	–3.50	Anisometropia and strabismus (left eye)	63
07	21	Female	0.02	–6.50/–1.25×5	0.34	–4.50/–1.25×170	Anisometropia (right eye)	100
08	18	Female	0.43	–0.25/+2.50×90	0.16	–4.50/+1.75×90	Anisometropia and strabismus (left eye)	100
09	18	Female	0.44	+1.50/+1.00×135	0.06	–3.50	Anisometropia (left eye)	50
10	20	Female	0.14	–2.00/+0.50×175	0.81	+1.00/+0.50×65	Anisometropia and strabismus (right eye)	> 400
11	26	Male	0.21	+5.50/+0.50×120	0.29	+8.50/+0.75×50	Anisometropia and cataract (both eyes)	100
12	18	Female	–0.24	–1.25	0.22	+1.50/+1.25×20	Anisometropia (right eye)	100
13	16	Female	0.84	+3.50/+2.00×135	–0.19	–0.75	Anisometropia (left eye)	200
14	28	Male	0.18	+9.00	0.29	9.00/+1.00×130	Anisometropia (both eyes)	100
15	19	Female	0.39	+1.25/+1.00×120	–0.11	–4.00	Anisometropia (left eye)	40
16	35	Female	1.0	+5.00/+0.50×85	–0.21	–0.25	Anisometropia (left eye)	400
17	24	Female	0.87	+5.25/+1.00×95	–0.26	+0.50/+0.50×15	Anisometropia and strabismus (left eye)	100
18	25	Female	0.35	+2.50/+0.75×85	–0.4	–3.00/+0.50×165	Anisometropia (left eye)	40

Note: logMAR = logarithm of minimum angle of resolution.
[a]Visual acuity was evaluated with the FrACT (Bach, 1996). [b]Stereo acuity was assessed with the Titmus Stereo Test (Stereo Optical Co., Inc., Chicago, IL).

Ebbinghaus illusion (Experiment 2c). Adaptation training reduced the magnitude of the Ebbinghaus illusion (see Fig. 5b) when the inducers and test circle were presented to the same eye (i.e., monocular condition). In the dichoptic condition, the illusion was not affected much, except when the weaker eye was tested at the 24-hr follow-up. Specifically, in the monocular condition, we observed a reduction in the magnitude of the illusion for both eyes in all the posttests. Results for the weaker eye were as follows—24-hr posttest, $t(8) = 3.74$, $p = .006$, $d = 1.25$, 95% CI = [–0.07, –0.02]; 2-week posttest: $t(8) = 5.27$, $p < .001$, $d = 1.76$, 95% CI = [–0.07, –0.03]; 4-week

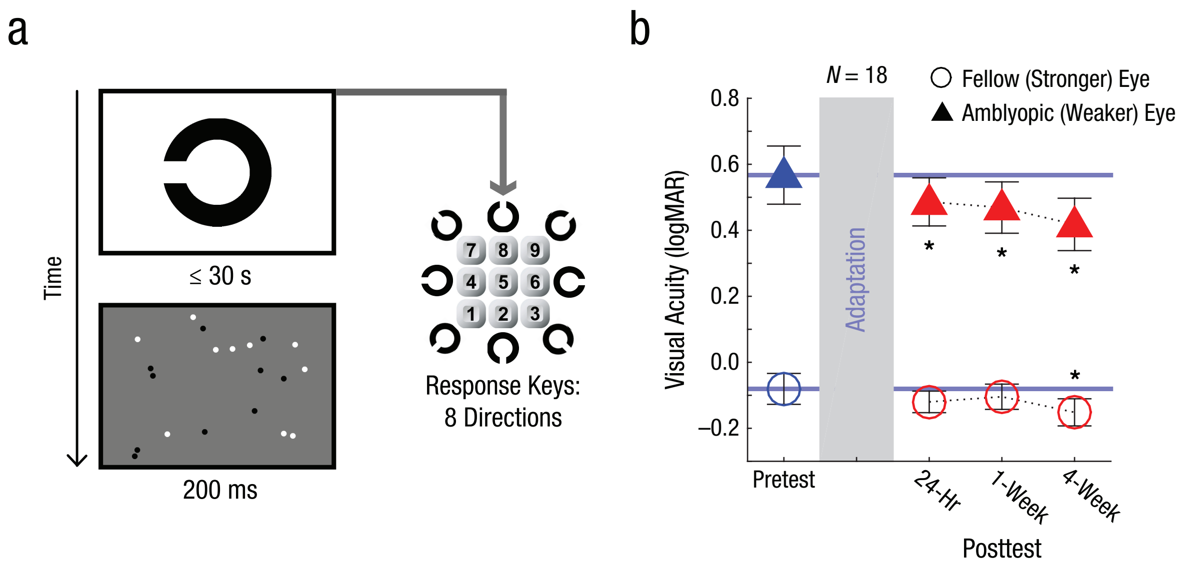

Fig. 9. Experiment 3 (visual acuity): illustration of the task and results. On each trial (a), a Landolt C in one of eight orientations was presented for up to 30 s, and the task was to indicate its orientation (eight-alternative forced-choice task). The displays were viewed with an opaque patch covering one eye. Each eye was tested in a separate block. A display of randomly placed black and white dots was presented for 200 ms at the end of each trial to eliminate any afterimage. The graph in (b) shows grand-average visual acuity of the fellow eye (or stronger eye, in the case of bilateral amblyopia patients) and the amblyopic eye (or weaker eye, in the case of bilateral amblyopia patients) at the pretest and each of the posttests. Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$).

posttest: $t(8) = 5.29$, $p < .001$, $d = 1.76$, 95% CI = [−0.06, −0.02]; 8-week posttest: $t(8) = 3.63$, $p = .007$, $d = 1.21$, 95% CI = [−0.08, −0.02]. In the dichoptic condition, we found a significant immediate reduction (24-hr posttest) in the magnitude of the illusion when the test circle was presented to the weaker eye, $t(8) = 3.40$, $p = .009$, $d = 0.95$, 95% CI = [−0.05, −0.01].

In the control group, the magnitude of the illusion was also reduced in the monocular condition (weaker eye: all *p*s < .05; stronger eye: $p < .05$ at the 2-week

Table 2. Comparison of the Effect Sizes (Cohen's *d*) in the Adaptation and Control Groups in Experiment 2

	Posttest		
Effect	24-hr	2-week	4-week
Dichoptic motion coherence			
Stronger eye	√	x	x
Weaker eye	√	√	—
Visual acuity			
Stronger eye	√		√
Weaker eye	√		√
Ebbinghaus illusion: dichoptic condition			
Stronger eye	x	x	x
Weaker eye	√	x	x
Ebbinghaus illusion: monocular condition			
Stronger eye	√	√	√
Weaker eye	√	√	√
Interocular phase combination	x	x	√
Interocular grouping	√	x	x
Stereo sensitivity	x		x

Note: An *x* indicates that the effect was nonsignificant in the adaptation group ($p \geq .05$). A checkmark indicates that the effect size was at least medium (i.e., $d \geq 0.5$; Cohen, 1992) in the adaptation group and also larger in the adaptation group than in the control group, and a dash indicates that the effect size was at least medium in both groups but larger in the control group than in the adaptation group.

posttest only; see Fig. 5b for results in both conditions). However, as shown in Table 2, the effect sizes in the control group were smaller than those in the adaptation group. Therefore, the reduction of the illusion's magnitude in the adaptation group cannot be explained as a general learning effect.

Interocular phase combination (Experiment 2d). Five days of adaptation training did not lead to immediate changes in the perceived phase angle in this task, $t(8) = -0.50$, $p > .250$, $d = 0.17$, 95% CI = [−0.30, 0.46] (see Fig. 6b). However, the perceived phase angle reduced toward zero in the following posttests, which indicated that the two eyes became increasingly balanced during the subsequent 2 months of everyday life. This effect was not yet significant after 2 weeks, $t(8) = 1.69$, $p = .129$, $d = 0.56$, 95% CI = [−1.74, 0.27], but became significant after 4 weeks, $t(8) = 2.94$, $p = .019$, $d = 0.98$, 95% CI = [−2.40, −0.29], and remained significant after 8 weeks, $t(8) = 2.53$, $p = .035$, $d = 0.84$, 95% CI = [−2.90, −0.13].

No significant changes in the perceived phase angle were observed in the control group (all ps > .11; see Fig. 6b). Thus, the effect size was greater in the adaptation group than in the control group at the 4-week posttest (see Table 2).

Interocular grouping (Experiment 2e). Interocular grouping was slightly affected by the adaptation training, but only immediately after the end of the training (24-hr posttest), $t(8) = 2.32$, $p = .049$, $d = 0.77$, 95% CI = [0.00, 0.31] (see Fig. 7c). No significant effects were observed in the control group (all ps > .34; Fig. 7c).

Stereo sensitivity (Experiment 2f). In the adaptation group, we observed a marginally significant increase in stereo sensitivity immediately following the adaptation training (24-hr posttest), $t(8) = 2.24$, $p = .055$, $d = 0.75$, 95% CI = [−3.03, 0.04] (see Fig. 8b). In the control group, a significant improvement in stereo sensitivity was observed after 4 weeks, $t(9) = 2.32$, $p = .045$, $d = 0.73$, 95% CI = [−1.98, −0.03] (see Fig. 8b).

Experiment 3

Visual acuity. After adaptation to the patchwork images for seven daily sessions, the visual acuity (logarithm of minimum angle of resolution, or logMAR) of patients' amblyopic eyes (or the weaker eyes, in the case of the bilateral amblyopia patients) was immediately improved from 0.567 to 0.486 (24-hr posttest), $t(17) = 3.63$, $p = .002$, $d = 0.86$, 95% CI = [−0.13, −0.03] (see Fig. 9b). More important, this effect strengthened during the subsequent month of living in the normal visual environment. Specifically, visual acuity improved to 0.469 after 1 week, $t(17) = 4.37$, $p < .001$, $d = 1.03$, 95% CI = [−0.15, −0.05], and further improved to 0.418 after 4 weeks, $t(17) = 4.34$, $p < .001$, $d = 1.02$, 95% CI = [−0.22, −0.08]. Therefore, on average, the visual acuity of the amblyopic eye (or the weaker eye) was improved by 0.149 (logMAR), or around 1.5 lines on the logMAR eye chart. When we removed the data from the 2 bilateral amblyopia patients, the grand average improvement for the amblyopic eye reached 1.6 lines (see Fig. S9 in the Supplemental Material).

Significant improvement in visual acuity of the fellow eye (or stronger eye, in the case of the bilateral amblyopia patients) was observed only at 4 weeks after the end of adaptation training (from −0.081 to −0.152, or 0.71 lines on the logMAR chart; see Fig. 9b), $t(17) = 3.12$, $p = .006$, $d = 0.73$, 95% CI = [−0.12, −0.02].

Stereo acuity. No significant improvement in stereo sensitivity was found at any of the posttests (see Fig. S10 in the Supplemental Material)—24-hr posttest: $t(17) = 0.19$, $p > .250$, $d = 0.05$, 95% CI = [−96.92, 80.70]; 1-week posttest: $t(17) = 0.55$, $p > .250$, $d = 0.13$, 95% CI = [−92.98, 54.42]; 4-week posttest: $t(17) = 1.70$, $p = .11$, $d = 0.40$, 95% CI = [−122.95, 13.29].

Contrast sensitivity. Contrast sensitivity was measured for each of seven specified spatial frequencies at each session. Therefore, a contrast sensitivity function (CSF) could be delineated for each eye in each session (see Fig. 10a). The peak sensitivity (see Fig. 10b) and the corresponding spatial frequency in each CSF were identified. For the amblyopic (or weaker) eye, there was a nonsignificant trend of increased peak sensitivity 24 hr after adaptation training, $t(17) = 1.47$, $p = .159$, $d = 0.35$, 95% CI = [−2.35, 13.23], and also 1 week after adaptation training, $t(17) = 1.59$, $p = .130$, $d = 0.37$, 95% CI = [−2.72, 19.39]. A significant increment in peak sensitivity was observed at the 4-week posttest, $t(17) = 2.78$, $p = .013$, $d = 0.66$, 95% CI = [3.34, 24.36].

We also analyzed the areas under the curve (AUCs; see Fig. 10c). Immediately following the training, the AUC increased significantly for the amblyopic (or weaker) eye, $t(17) = 2.57$, $p = .020$, $d = 0.61$, 95% CI = [6.20, 62.56]. The AUC also increased significantly for the fellow (or stronger) eye at the 1-week posttest, $t(17) = 2.91$, $p = .010$, $d = 0.69$, 95% CI = [19.62, 122.64]. Other results for the AUC were not significant (amblyopic or weaker eye: all ps > .20; fellow or stronger eye: all ps > .07).

No significant shift in the spatial frequency of peak sensitivity was found in the CSFs (amblyopic or weaker eye: all ps > .250; fellow or stronger eye: all ps > .09).

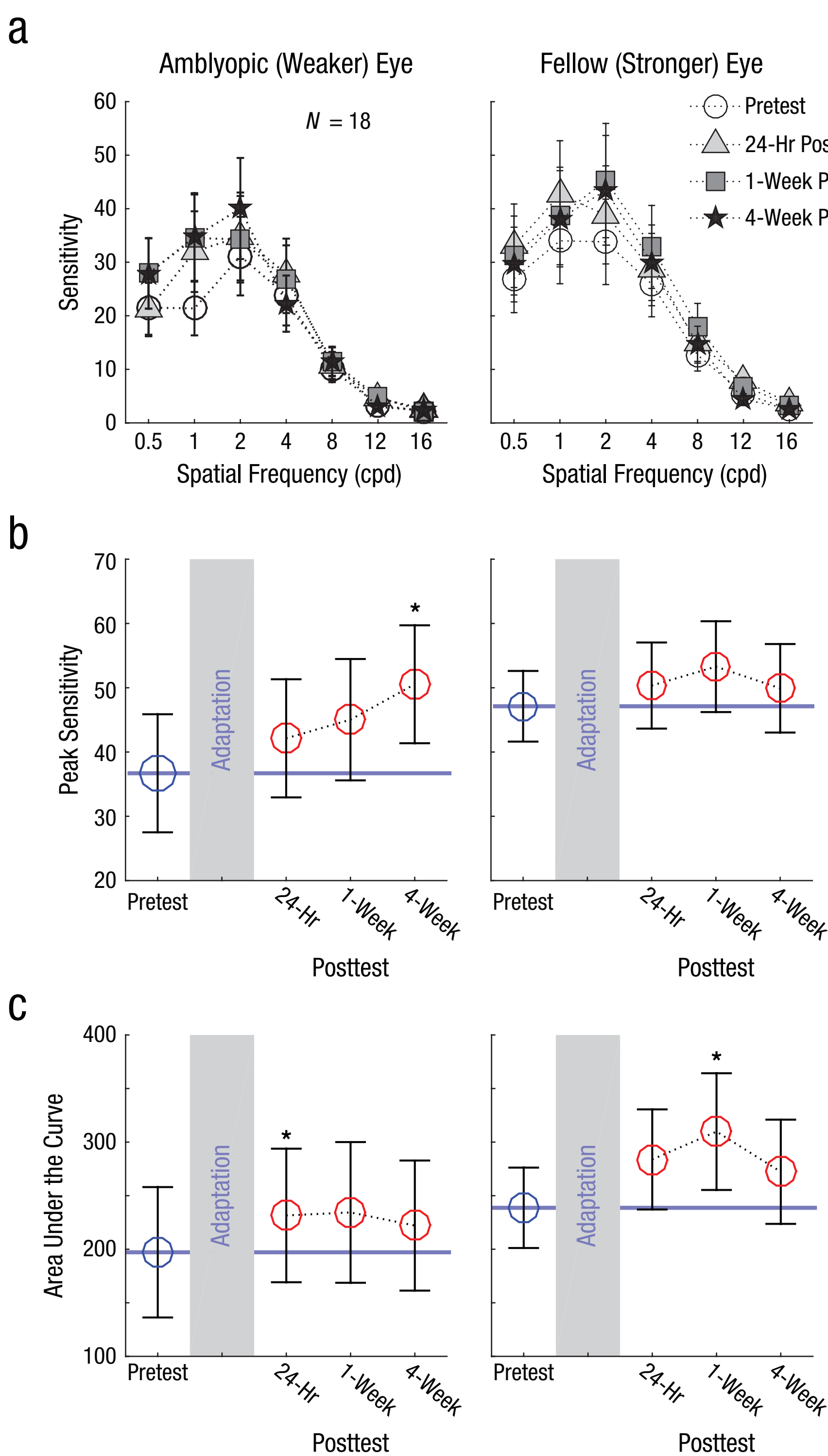

Fig. 10. Results from Experiment 3 (contrast sensitivity): (a) contrast sensitivity functions, (b) peak sensitivity, and (c) area under the curve for the pretest and each of the posttests, separately for the amblyopic (or weaker) eye (left) and for the fellow (or stronger) eye (right). Error bars represent ±1 *SEM*. Asterisks indicate significant differences from the pretest ($p < .05$). cpd = cycles per degree.

Discussion

We used a novel method to reduce sensory ocular dominance through long-term adaptation in human adults. Three hours of adaptation produced effects lasting for a week (see Supplemental Experiment 1, in the Supplemental Material). Five such sessions over successive days produced increasingly large effects (Experiment 2) and triggered surprising additional strengthening over the subsequent 2 months, when subjects experienced natural vision only.

Long-lasting aftereffects of relatively short-duration adaptation are mainly found for adaptation to complex patterns (Carbon & Ditye, 2011; Jones & Holding, 1975). More directly comparable with the current work are studies investigating hours-long contrast adaptation (4 hr) and monocular deprivation (2.5 hr). However, the aftereffects in those studies were much more short-lived than those in the current study, decaying to baseline within a few hours (Lunghi et al., 2013; Zhang, Bao, Kwon, He, & Engel, 2009). In general, adaptation may be controlled by multiple mechanisms with differing time scales (Bao & Engel, 2012; Bao, Fast, Mesik, & Engel, 2013; Mei, Dong, & Bao, 2015), and sensitivity is proportional to the sum of the outputs of multiple controllers, each operating over its own preferred time scale. According to this account, the rapid decline of most adaptation effects may reflect faster processes "de-adapting" and masking residual adaptation arising from slower processes. One possible explanation for the long-lasting aftereffects we observed is that relatively rapid processes do not contribute to interocular balance, given that physical inputs to the two eyes do not naturally vary much over the short term.

Alternatively, the neural mechanisms that produced our results may more closely match those underlying perceptual learning, which more frequently produces long-lasting effects (Karni & Sagi, 1993). The increased interocular balance we observed over 5 days of adaptation is consistent with this idea.

But unexpectedly, subjects' interocular balance continued to increase over 2 months of living in the normal visual environment. Similar posttraining strengthening was also revealed by other measurements of visual functioning (e.g., interocular phase combination) in both subjects without amblyopia and those with amblyopia. This pattern of results is clearly inconsistent with reports that effects of adaptation, whether short-lived or persistent, always start to decay toward the baseline immediately after the end of adaptation. However, perceptual learning does not often improve after training has stopped either (Karni & Sagi, 1993). It is possible that the improvements at the posttests (which we refer to as *late learning*) and those during and immediately after training were driven by different mechanisms. In Experiment 1, subjects' improvement during training correlated relatively strongly with their initial interocular imbalance ($r = -.96$, $p < .001$), but their late learning did not ($r = .10$, $p = .78$; see Fig. 2c and the Supplemental Material).

What caused the learning after the end of training remains an open question. We speculate that the adaptation training may have altered the visual system in some way so as to reactivate a preexisting mechanism of ocular-dominance plasticity that works on natural visual input. Adaptation to the patchwork images may have reduced the mutual inhibition between the two eyes' inputs, and especially the inhibition of inputs from the weaker eye by the inputs from the stronger eye. This in turn could have facilitated the ability of the weaker eye to increase neural gain during everyday activity.

This speculation receives at least some support from the observation in Experiment 2c that the Ebbinghaus illusion weakened after adaptation training. Although not always labeled as such, the Ebbinghaus illusion is an index of visual surround suppression, an adaptive process in which the sensory system optimizes information processing to consider the visual context, such that perception of an object is biased by its surround (or context). The Ebbinghaus illusion has been found to be weaker in subjects with schizophrenia than in healthy control subjects (Tibber et al., 2013). Interestingly, weaker surround suppression in schizophrenia has been shown to correlate with reduced gamma-aminobutyric acid (GABA) concentration (Yoon et al., 2010). Furthermore, reduced GABA concentration in primary visual cortex has also been found following monocular deprivation, which plausibly indicates a deprivation-induced disinhibition between the two eyes' inputs (Lunghi, Emir, Morrone, & Bridge, 2015). Considering the findings in all this work, the weakening of the Ebbinghaus illusion after the adaptation training likely reflects reduced GABA concentration, which we hypothesize led to disinhibition between the two eyes' inputs.

The results for dichoptic motion coherence, visual acuity, and interocular phase combination all indicated that the visual functioning of the weaker eye was improved by the adaptation training. However, we found no significant effects on stereo sensitivity, the strongest effect on interocular grouping was a marginally significant effect immediately after training, and interocular phase combination was not affected until the 1-month posttest. Therefore, we infer that adaptation to the patchwork images predominantly modulates the mechanisms for interocular competition and suppression, having limited influence on binocular

Table 3. Comparison of Some Recently Studied Methods for Treating Imbalanced Ocular Dominance

Study	Subject group	Approach	Length of induction	Duration of effects after induction	Patching needed	Potential risk of addiction	Effects tuned to limited spatiotemporal features	Lab needed	Everyday life (e.g., work) interrupted
Levi & Polat (1996)	Adult patients	Perceptual learning	5–8 runs	> 5–8 runs	Yes (fellow eye patched)	No	Yes	Yes	Yes
Polat, Ma-Naim, Belkin, & Sagi (2004)	Patients (9–55 years old)	Perceptual learning	~45 runs, 30 min each (2–4 weeks)	> 12 months	Yes (fellow eye patched)	No	Yes	Yes	Yes
Thompson, Mansouri, Koski, & Hess (2008)	Adult patients	Repetitive transcranial magnetic stimulation	15 min	> 24 hr for 1 of 3 patients	No	No	No	Yes	Yes
Hess, Mansouri, & Thompson (2010)	Adult patients	Perceptual learning	2–6 weeks	Not reported	No	No	Yes	Yes	Yes
Xu, He, & Ooi (2010)	Adult nonpatients	Perceptual learning	2 hr/day for 10 days	Not reported	No	No	Yes	Yes	Yes
R. W. Li, Ngo, Nguyen, & Levi (2011)	Adult patients	Video-game playing	2 hr/day for 20–40 days	Not reported	Yes (fellow eye patched)	Yes	No	No	Yes
J. Li et al. (2013)	Adult patients	Video-game playing	1 hr/day for 2 weeks	> 3 months	No	Yes	No	No	Yes
Ooi, Su, Natale, & He (2013)	Adult patients	Perceptual learning	7–15 runs, 1.5 hr each	> 4–8 months	No	No	Yes	Yes	Yes
Lunghi, Burr, & Morrone (2013)	Adult nonpatients	Adaptation	2.5 hr	> 180 min	Yes (stronger eye patched)	No	No	No	No
Zhou, Thompson, & Hess (2013)	Adult patients	Adaptation	2.5 hr	> 60 min	Yes (amblyopic eye patched)	No	No	No	No
Present study (Experiment 1)	Adult nonpatients	Adaptation	3 hr/day for 5 days	> 4 months (with strengthening for the first 2 months after adaptation training ceased)	No	No	No	No	No

integration (Kovacs, Papathomas, Yang, & Feher, 1996). Moreover, Experiment 3 demonstrates that our method can be used to improve the vision of patients with amblyopia. The adults with unilateral amblyopia had their amblyopic eyes' visual acuity improved by 1.6 lines on the logMAR chart after only seven daily adaptation sessions.

Several other approaches have been developed to influence the ocular dominance of adults. Some are based on monocular eye patches, used either passively or in conjunction with laboratory-based training (R. W. Li, Ngo, Nguyen, & Levi, 2011; Lunghi et al., 2013; Polat et al., 2004). Our method instead relies on a task that demands increased binocular cooperation, an approach also adopted by other research groups (Hess, Mansouri, & Thompson, 2010; Ooi, Su, Natale, & He, 2013; Spiegel et al., 2013; Thompson, Mansouri, Koski, & Hess, 2008; Xu, He, & Ooi, 2010). A novel finding of the present study is that the interocular balance achieved through training can be very long-lasting. Experiment 1 suggests that our method results in interocular rebalancing not only during the adaptation training stage, but also in the following 2 to 4 months of living in the normal visual environment. This suggests the possibility that treatments involving relatively short periods of adaptation training spaced between periods of natural viewing will produce large effects.

The adaptation-based eye-patch method has been shown to produce larger effects on binocular rivalry than our method did (Bai, Dong, He, & Bao, 2017; Lunghi et al., 2013). However, the effects of eye patching are much shorter lasting. With regard to clinical application, a large but short-lived effect is less appealing than a smaller but longer-lasting effect (that strengthens over time under natural viewing conditions). Moreover, other methods (e.g., Lunghi et al., 2011; Ooi et al., 2013) boost one eye only, and this carries the risk of reversed ocular dominance under prolonged application. By contrast, our method balances the deprivation (or training) of the two eyes and encourages the use of both eyes. This guarantees reshaping of ocular dominance toward balance between the eyes. Therefore, prolonged application of our method is not likely to cause reversed ocular dominance. This is another advantage of our method, especially for patients with mild and medium levels of amblyopia.

The most important advantage of our method is that it should eventually be usable by patients outside the laboratory, during their everyday activities, a convenience that many other methods cannot offer (see Table 3 for a comparison of some past methods with ours). This advantage also allows patients to achieve interocular balance during voluntary physical activity, which has been found to further boost ocular-dominance plasticity (Lunghi & Sale, 2015). Training on specific tasks transfers only partially to other tasks, which poses difficulties for therapy with traditional perceptual-learning methods (Levi & Li, 2009). This problem gets worse as training continues over time, as the visual system may adopt more and more specialized changes to improve task performance, a phenomenon that is analogous to overfitting of statistical data (Sagi, 2011). Such overfitting may limit the size of effects producible by traditional approaches, but should not affect long-term interventions using our method.

Action Editor

Alice J. O'Toole served as action editor for this article.

Author Contributions

M. Bao designed and engineered the altered-reality system and conceived the study. M. Bao, B. Dong, S. A. Engel, and Y. Jiang designed the experiments. B. Dong and L. Liu performed the experiments, and M. Bao and B. Dong analyzed the data. M. Bao wrote the manuscript, and S. A. Engel and Y. Jiang revised it.

Declaration of Conflicting Interests

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

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Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/0956797617728126

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