# Supporting Information

## Bao and Engel 10.1073/pnas.1113503109

### SI Materials and Methods

**Experiment 1.** ***Subjects.*** Sixteen observers, 15 of whom were naïve to the experiment's hypotheses, participated in experiment 1. Seven subjects participated in experiment 1a, which measured effects of long adaptation durations. Four of these subjects, along with four new subjects, participated in experiment 1b, which measured effects of contrast enhancement. Two of the subjects from experiment 1a and five new subjects, participated in experiment 1c, which tested short adaptation durations. All subjects had normal or corrected to normal vision. Experimental procedures were approved by the University of Minnesota Institutional Review Board.

***Hardware.*** The altered reality system is comprised of a camera connected to a laptop computer that feeds into a head-mounted display (HMD). Hardware details are reported in ref. 1.

***Image acquisition, filter design, and image processing.*** We developed custom software to process the image that was acquired and displayed by MATLAB (Mathworks) toolboxes (2). The camera images (752 × 480; 8 bits grayscale at 30 Hz) were cropped to 640 × 480 resolution and then filtered in real-time on the graphics processing unit (GPU). The images were filtered in real time by multiplying the filter with captured image in the Fourier domain (mathematically equivalent to convolution), and the inverse FFT of the resultant was displayed (1).

The filter was a second-order Butterworth filter centered at 1.5 cycles per degree and 90° of orientation (vertical). The filter cutoffs were 0.3 cpd to 7.8 cpd in spatial frequency and 90 ± 37° in orientation; filter strength fell to <2% of maximum outside this range. Fig. 2 *A* and *B* show the original and filtered image, respectively. Note the maintenance of contours at other orientations.

***Adaptation conditions.*** All subjects in experiments 1a and 1c viewed images of the world filtered to remove vertical energy. Subjects wore the system for multiple durations, which were 1, 4, and 8 h in experiment 1a and 1, 3, 10, and 30 min in experiment 1c, during which time they performed everyday tasks of their choosing, including playing manual and video games, watching movies, taking walks, and eating, among other activities.

Subjects completed two repetitions of 1, 4, and 8 h of adaptation in experiment 1a, and four repetitions of 1, 3, 10, and 30 min adaptation in experiment 1c. Repetitions were separated by at least 1 d for experiment 1a and at least 30 min for experiment 1c. The order of the conditions within each experiment was counterbalanced.

***Enhancement conditions.*** Subjects in experiments 1b viewed images of the world filtered to enhance vertical energy. Subjects completed two 4-h sessions. Images were constructed by using the inverse of the filter shape as for deprivation. This filter was set to have a value of 2 at its maximum, effectively doubling vertical energy, and a value of 1 beyond its cutoffs, which left other orientations relatively intact.

***Tilt aftereffect measurements. Stimuli.*** Stimuli were plaid patches made up of two 1.5 cpd sine-wave gratings symmetrically tilted relative to vertical. Patch edges were smoothed with a Gaussian filter. The patches subtended 5° of visual angle and were centered at fixation. Subjects were both adapted and tested on the HMD display. Luminance on the HMD was calibrated by using a PR-655 spectrophotometer; gamma curves were measured and corrected in software. To limit exposure to horizontal and vertical edges, testing took place within an elliptical aperture on the HMD, which was constructed by simply setting pixels outside the ellipse to black.

***Task.*** We used the tilt aftereffect (TAE) to measure how subjects adapted to being deprived of vertical energy. We adopted a paradigm first introduced by Meese and Georgeson (3) in which the TAE could be investigated without presenting the adapted (vertical) orientation. The stimulus (detailed above) was a plaid made from two 45° gratings, which perceptually resembled a blurred square checkerboard. A TAE from adaptation to vertical causes the component grating to appear symmetrically tilted relative to 45°, which, in turn, causes the checks to appear rectangular. After adaptation, subjects were given control of the physical tilt of the gratings, and adjusted them to cancel out any TAE. The physical tilt required to cause the checks to appear square was recorded as our measure of the TAE.

During each trial, a plaid was repeatedly flashed on the center of the midgray background (100-ms presentation) followed by 2-s mean field presentation. Subjects adjusted the tilt of the components from a random initial angle through button presses, which controlled the appearance of the plaid on its subsequent presentation. Subjects continued this flash-adjustment sequence until the checks appeared square, which was indicated by a final button press. Each subject completed 40 trials before and 60 trials after adaptation. Both the final physical orientation of grating components and response time in each trial were recorded. The average time to complete a trial was 8.8 ± 3.7 s, which roughly equals four stimulus presentations.

***Analysis.*** The 40 responses in the pretest trials were averaged to estimate a baseline for each session, the tilt of the gratings that created square checks before adaptation. After adaptation, the 60 responses were concatenated and baseline subtracted to form a timeseries of the TAE effect due to adaptation. The timeseries was smoothed with a five-trial moving average and then nearest-neighbor interpolated to 5-s sample intervals. Separate timeseries were constructed for each session and averaged across repetitions of each adaptation duration. To test whether longer adaptation durations produce larger TAEs, we measured the strength of the TAE as the mean of the first 10 s of the posttest for each duration. These means were then entered into a standard within-subjects linear trend analysis.

**Experiment 2.** ***Subjects.*** Twelve observers participated in experiment 2. All had normal or corrected to normal vision. Experimental procedures were approved by the University of Minnesota Institutional Review Board.

***Adaptation conditions.*** The same altered reality system was used as in experiment 1, programmed to perform the same filtering operation, removal of vertical energy. In this experiment, we also used the system in a "see-through" mode, where unfiltered camera images were displayed.

The adaptation protocol had several stages (Fig. 5*B*) all completed in succession without breaks. Subjects: (*i*) Viewed unfiltered images for 15 min. (*ii*) Completed an initial set of tilt-aftereffect measurements, termed baseline. (*iii*) Adapted (to vertical deprivation) using the altered reality system for 8 min, the initial adaptation. (*iv*) Completed a second set of tilt aftereffect measurements, the pre-test. (*v*) Adapted for 4 h. (*vi*) Viewed unfiltered images for 15 min, the deadaptation period. (*vii*) Completed a third set of tilt aftereffect measurements, the deadaptation test. (*viii*) Adapted for a second 8-min period. (*ix*) Completed a final set of TAE measurements, the post-test.

***Stimuli.*** Stimuli were identical to those used in experiment 1.

***Task.*** The tilt aftereffect was measured, as in experiment 1, but in this experiment, we adopted a one-down, one-up staircase procedure rather than an adjustment paradigm. Each trial started with a 0.6-s mean field presentation. A plaid was then presented for 100 ms followed by a second mean field presentation for 1.8 s. Subjects indicated with a button press whether the checks appeared elongated horizontally or vertically. The staircase procedure then adjusted the orientation of the plaid component gratings to null the subject's perceived elongation. The step size of the adjustment was 2° in the beginning of the staircase and was reduced to 1.125° after three reversals. After another three reversals, the step size was further reduced to 0.25°.

The staircase for the baseline measurements began with a plaid presentation with 45° components. Subjects' baseline unadapted state was estimated by the mean of the last 15 reversals of the baseline staircase. All staircases in subsequent tests started from this common baseline.

***Analysis.*** The orientation of the plaid component gratings were recorded as measures of the TAE. The baseline value was subtracted from each data point, and the successive orientations in a given test session formed a timeseries of data. Data for the first few reversals of the staircase were relatively unstable, because large step sizes were used to allow quick convergence near perceived values. Accordingly, points in the timeseries before the sixth reversal were removed and replaced with two values: the means of the first, and second three sets of reversals placed at the mean response time of each set. The timeseries were then nearest-neighbor interpolated to 2-s intervals.

## SI Effects of Deadaptation upon Nondeprived Mechanisms

In recent models of orientation processing, output from neurons tuned to one orientation is inhibited, or "normalized," by an amount proportional to the pooled output of other neurons, and this normalization pool is likely affected by adaptation (4). In theory, deprivation of vertical could reduce the amount of inhibition received by horizontal neurons, leading them to be more active, and adapt by reducing their responsiveness over time. Our prior study (ref. 1, experiment 2), suggests that this effect did not occur for deprivation by showing that, under certain conditions, deprivation decreased detection thresholds for the deprived orientation while leaving thresholds for the orthogonal orientation unchanged.

However, normalization pools could have been affected by our deadaptation paradigm. The hypothesis is that during deadaptation, vertical neurons, whose gain has been raised by deprivation, will fire robustly, which would lead to more activity in the normalization pool of horizontal cells. Hence, during deadaptation, horizontal neurons should respond less than normal and, accordingly, adapt by increasing their responsiveness.

To test this possibility, we simulated our deadaptation conditions by exposing subjects to natural images where vertical energy had been dramatically increased. Subjects viewed 15-min video clips in which vertical energy had been tripled, using the filtering methods described in our paper. Adaptation raised detection thresholds for vertical, as expected, and left thresholds for horizontal either untouched or slightly raised. These results suggest that deadaptation did not cause horizontal neurons to increase their responsiveness, because that would have decreased horizontal detection thresholds.

**Subjects.** Three observers, one of whom was naïve to the experiment's hypotheses, participated in the experiment. All subjects had normal or corrected to normal vision. Experimental procedures were approved by the University of Minnesota Institutional Review Board.

**Stimuli and Display.** Subjects viewed 15-min video clips from a popular TV show, presented on a calibrated CRT display controlled by a 14-bit video card (Bits++, Cambridge Research Systems). The display was matched in visual angle to the size of the HMD's display used in the experiments reported in the main body of the paper. Images were filtered by using the identical filter as used in those experiments. The CRT display was surrounded by a cylindrical tube lined with black felt, in which subjects placed their heads, to restrict viewing to the filtered images.

**Adaptation Conditions.** In a baseline condition, subjects viewed 15-min of video in which the contrast of each frame was reduced by 50%. In the adaptation condition, subjects viewed video in which each frame was first reduced by 50% and then filtered to enhance vertical energy by a factor of 3 using the methods described in the main body of the paper.

**Threshold Measurements.** On each trial, subjects viewed foveally presented circular sinusoidal grating patches that subtended 8°. The orientation of the grating was either horizontal or vertical, selected randomly on each trial. The gratings increased their contrast from near zero to 2.5% over a period of 3 s. Subjects were instructed to press a button when the grating was just visible to them. The grating display terminated when the subject responded. A tone marked the start of each trial, and a randomly selected delay between the tone and the grating presentation was included to prevent subjects from responding on the basis of timing information.

In each session, 24 horizontal and 24 vertical trials, on average, were presented both after the baseline and the filtered adaptation, each over a period of 75 s. Subjects completed between 7 and 10 sessions.

**Analysis.** The stimulus contrast at the time of response was taken as a measure of threshold. Thresholds for vertical and horizontal stimuli were sorted to yield two timecourses of data. Responses fell at slightly different times from trial to trial, and so for display purposes, the timecourses were smoothed slightly (filter size = 10 s) and interpolated to yield a timecourse of thresholds sampled every 2 s, which were then averaged across sessions. The average timecourses were smoothed again (filter size = 10 s). For statistical comparisons, thresholds from the baseline condition were compared with thresholds from the adaptation conditions by averaging the raw data for the first 10 s of testing for each session and performing paired $t$ test on the averages.

**Effects of Deadaptation: Results and Discussion.** Simulated deadaptation did not affect the orthogonal orientation. Fifteen minutes viewing natural images with increased vertical energy had little effect upon thresholds for horizontal gratings, but raised thresholds for vertical substantially and reliably for each of our three subjects ($P < 0.02$ for vertical and $P > 0.1$ for horizontal for all three subjects individually). Fig. S1 plots changes in threshold after the baseline stimulus and the simulated deadaptation videos. Baseline thresholds averaged between 0.006 and 0.007, for all three subjects, for both vertical and horizontal.

These results suggest that vertical formed a relatively small part of the normalization pool for horizontal perceptual mechanisms, which left them unaffected by our simulated deadaptation. The data are limited in a number of ways, however. For example, suprathreshold measures might have yielded different results. Note also that our results do not mean that the neural circuitry underlying contrast normalization is not an important part of visual adaptation generally. They do argue, however, that our initial findings cannot be easily accounted for by models that include deadaptation affecting horizontal perceptual mechanisms to a great extent.

1. Zhang P, Bao M, Kwon M, He S, Engel SA (2009) Effects of orientation-specific visual deprivation induced with altered reality. *Curr Biol* 19:1956–1960.
2. Brainard DH (1997) The psychophysics toolbox. *Spat Vis* 10:433–436.
3. Meese TS, Georgeson MA (1996) The tilt aftereffect in plaids and gratings: channel codes, local signs and "patchwise" transforms. *Vision Res* 36:1421–1437.
4. Dhruv NT, Tailby C, Sokol SH, Lennie P (2011) Multiple adaptable mechanisms early in the primate visual pathway. *J Neurosci* 31:15016–15025.

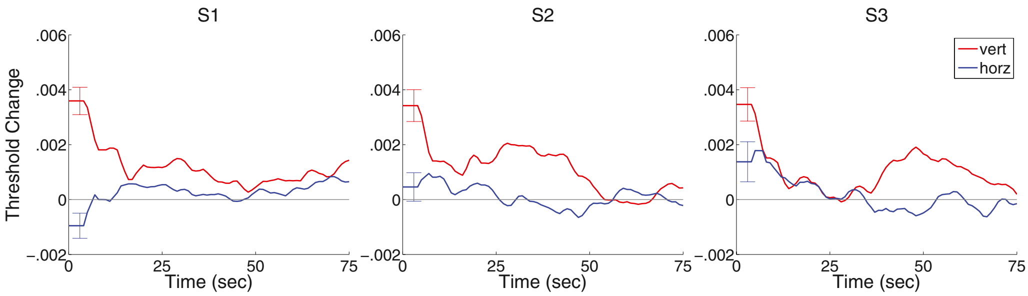


**Fig. S1.** Results of simulated deadaptation. The three graphs represent data from three subjects. In each, the enhanced orientation, vertical, shows reliable adaptation, whereas effects on the orthogonal orientation, horizontal, are small and unreliable.