Supplemental Data

The Scope and Limits of Top-Down Attention in Unconscious Visual Processing

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Supplemental Results

Spatial Attention with a Letter Task (1)

In the invisible condition of the spatial-attention experiment, we did not find any effects of attention. One could argue that the lack of attentional modulation is simply due to a failure of the observers to maintain attention to the spatial markers. To address this possibility, we conducted a control experiment in which spatial attention was explicitly manipulated by having the observers perform an attention-demanding task instead of relying on the instruction to observers. We presented rapidly changing streams of letters in the circles as illustrated in Figure S1A. The letter streams served as dichoptic masks and suppressed the visibility of the adaptors. The observers' task was to count the occurrences of the letter "X" at the location indicated before the beginning of a trial. The design of this experiment was identical to the spatial-attention experiment described in the main text except that attention was manipulated explicitly with the letter task. Only the invisible condition was tested. Twenty-four trials were conducted per condition.

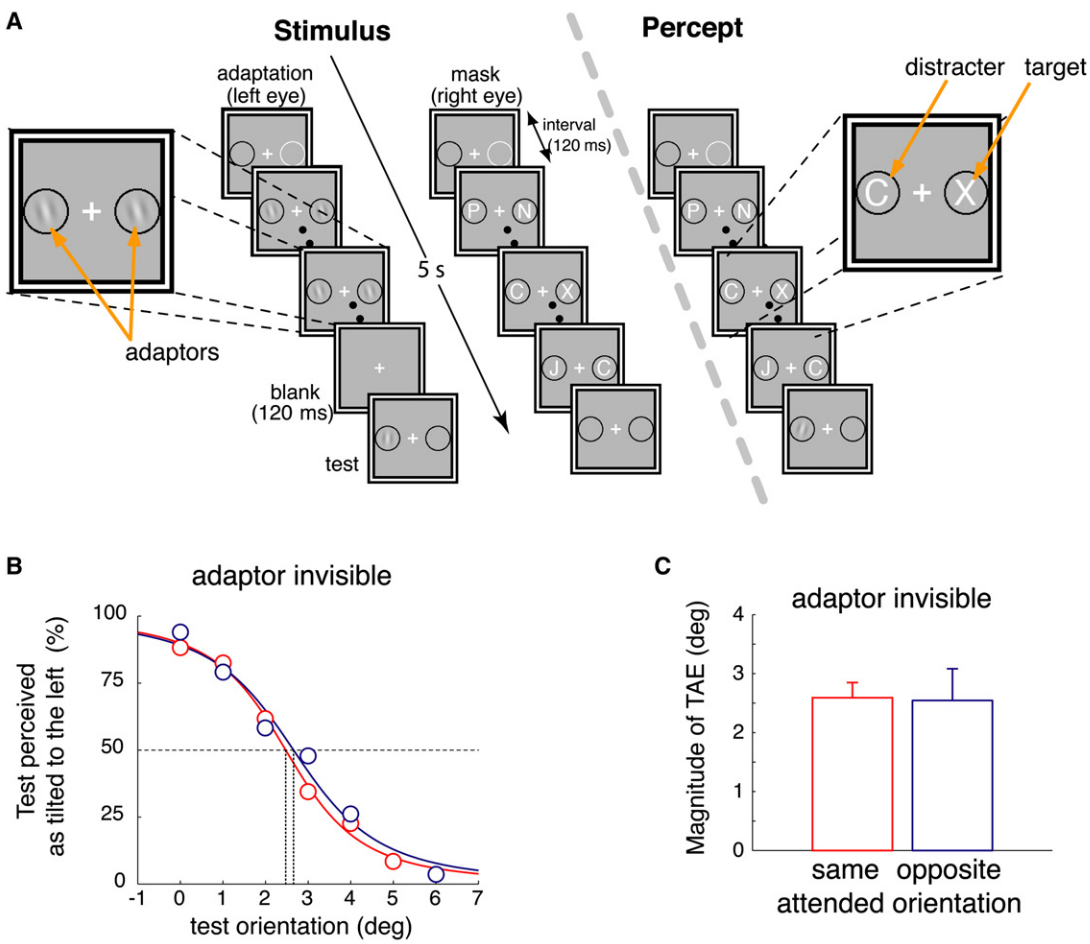

Figure S1. Stimuli and Results of Spatial Attention with the Letter Task

(A) Two streams of letters were shown on the right eye and the continuous change of the letters served as the dichoptic masks. The observers were required to count the occurrences of the letter "X" in the stream indicated by the white circle presented prior to each trial. The number of Xs was randomly varied between three, four, and five. On the other eye, two moving Gabors were presented at the corresponding locations.
(B) The results of the adaptor-invisible condition. The percentage of trials in which observers reported a tilt in the direction of TAE is plotted against the orientation of the test stimulus. The open red circles indicate the results of the condition in which the test was presented at the same location as the attended location, and the open blue circles indicate the condition in which the test was presented at the location opposite to the attended location.
(C) Summary of the results. Error bars indicate one SEM.

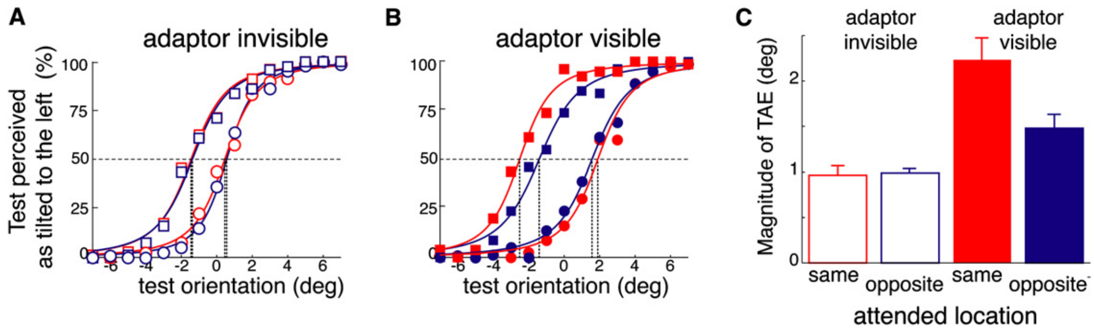

Figure S2. The Results of Spatial Attention with the Letter Task and Moving Gabors

(A) The results of the adaptor-invisible condition. The percentage of trials in which observers reported a left-tilt is plotted against the orientation of the test stimulus. On the x axis, left tilts are shown as positive values. The circles indicate the conditions where the adaptor was tilted to the left, and the squares indicate the conditions where the adaptor was tilted to the right. The red symbols indicate the conditions where the test was presented at the same location as the attended location, and the blue symbols indicate the conditions where the test was presented at the location opposite to the attended location.

(B) The results of the adaptor-visible condition.

(C) The TAE magnitude is shown per condition. The TAE was estimated for each observer as a half of the difference between the PSEs of the right-tilt adaptor and the left-tilt adaptor conditions. Error bars indicate the SEM of four observers.

The performance for the letter task was 75.6% ± 0.6% (SEM), and the only correct trials were used for the analysis. The results are shown in Figures S1B and S1C. The TAE magnitude was 2.59° ± 0.26° when attention was directed to the same location as the test, whereas it was 2.54° ± 0.53° when attention was directed to the opposite location. Even with the explicit attentional task, top-down spatial attention did not modulate the TAE for invisible adaptors (Figure S1B; two-tailed paired t test; $T(3) = 0.16$, $p = 0.92$).

Spatial Attention with a Letter Task (2)

In order to corroborate our conclusions from the spatial-attention experiments, we sought to obtain the TAE on a trial-by-trial basis by interleaving left-tilt adaptor and right-tilt adaptor across trials. In general, brief adaptation (5 s) yields a smaller magnitude of TAE, and this makes it difficult to discern the effects of attention. To obtain relatively large TAEs from brief adaptations, we used brief test stimuli (120 ms)—a manipulation known to result in larger TAE magnitudes [S1–S3]. The two adaptors had the same orientation to preclude the contribution of feature-based attention. The observers were asked to report the tilt direction of the test stimulus, the number of the target letter "X," and the visibility of the adaptors. The trials on which the adaptor became visible to the observers and the trials on which the observers made a mistake in the attentional task were removed from the analysis.

The second issue we aimed to address in this experiment is the effects of afterimages induced by stationary adapting stimuli. The intensity of afterimages is enhanced when attention is withdrawn from the inducer [S4, S5], whereas the intensity is reduced when the inducer is rendered invisible by CFS [S6]. If afterimages contribute to TAE in any way, the observed effects by attention and visibility in our main experiments might have been mediated indirectly through these effects. To exclude this possibility, we repeated the experiment with minimal afterimages by using slowly moving Gabors as adapting stimuli.

The results (Figure S2) confirm the findings of the main experiment. A significant TAE was found for both the invisible adaptors at the attended location (0.96° ± 0.09°; $T(3) = 5.58$, $p < 0.05$) and the unattended location (0.99° ± 0.05°; $T(3) = 5.44$, $p < 0.05$). Even with this explicit attentional task, top-down spatial attention did not modulate the TAE for invisible adaptors ($T(3) = 0.54$, $p = 0.63$). On the other hand, when the adaptors were visible, we found the expected significant attentional modulation (attend-same, 2.23° ± 0.25° versus attend-opposite, 1.48° ± 0.15°; $T(3) = 6.80$, $p < 0.01$).

These two control experiments demonstrate that directing attention to one location even with an explicit manipulation does not facilitate adaptation to an invisible stimulus at the attended location.

The Effects of Feature-Based Attention to Invisible Stimuli Are Not a Response Bias

In the feature-based-attention experiment, we found a significant attentional modulation for invisible adaptors. One could argue that if simply attending to a distant visible target were to cause a cognitive bias or nonlocal TAE, the difference in the TAE magnitude observed in the feature-based attention cannot be ascribed to direct interactions between top-down attention and the bottom-up unconscious signals from the masked adaptation stimuli. To control for this possibility, we conducted the same experiment but without the adapting stimuli behind the Mondrian patterns. The results of this control experiment (Figure S3) show that without an adapting stimulus at the test location, the attended orientation made no difference ($T(3) = 1.598$, $p > 0.05$) in orientation judgments depending on attended orientation (attend-left-tilt, 0.18° ± 0.28°; attend-right-tilt, 0.05° ± 0.26°).

It is possible that a very small TAE could be detected with a more sensitive method or a larger population of observers. Thus, we have added four new observers for this experiment to examine this possibility. Still no significant TAE was found for the total of eight observers; the mean difference between the attend-right-tilt and

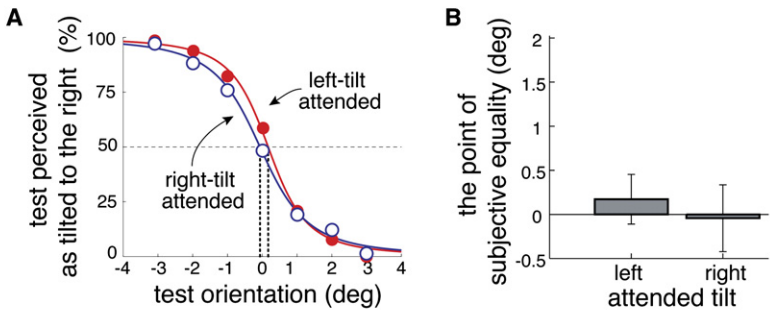

Figure S3. The Results of the Control Experiment for Feature-Based Attention

(A) The results of the adaptor-invisible condition. The solid red circles and the solid blue circles indicate the results for the attention to the left-tilt condition and attention to the right-tilt condition, respectively. The percentage of trials in which the observers reported a right tilt is plotted as a function of the test orientation (positive values indicate a left tilt).
(B) The point of subjective equality is shown per condition. The positive values correspond to the right tilt. Error bars indicate one SEM across the same four observers that participated in the main feature-based-attention experiment.

attend-left-tilt conditions was 0.39° ± 0.20° (SEM of the eight observers). Even with a one-tailed paired t test, it did not differ significantly from 0° ($T(7) = 1.3356$, $p = 0.1117$). The point of subjective equality (PSE) for the attend-right-tilt condition was 0.53° ± 0.06° toward right, and the PSE for the attend-left-tilt adaptation was 0.27° ± 0.16° (also right tilt). Although the direction of the effect is consistent with the idea that TAE would be induced by the observers' attention to the orientation of a distant Gabor, the difference did not reach significance. Although we cannot completely rule out the possibility that the TAE could be induced in a nonretinotopic fashion, such effects seem too small to account for the attentional effect we found for the case where an adaptor physically existed; the difference in PSE between attend-right-tilt and attend-left-tilt conditions was 0.26° in the control experiment, whereas it was 0.81° in the main experiment. Therefore, the attentional modulation of TAE in the main condition is taken to reflect the effects of feature-based attention on unconscious bottom-up signals for the adapting stimulus.

Manipulating the Difficulty of Maintaining Attention to Feature-Based-Attention Targets

The difference between the spatial-attention experiment and the feature-based-attention experiment may come from a difference in the difficulty of maintaining attention to targets. We addressed this issue in the two experiments reported below.

First, we examined the possibility that the presence of two attentional targets on the same visual hemifield in the feature-based-attention experiment might have encouraged the observers to pay more attention to one of the targets. To control for this possibility, we repeated the feature-based attention presenting a single attention target on the right visual field.

The results of this control experiment (Figure S4) replicate those found in the main experiment. Regardless of the visibility of the adaptor, the TAE magnitude was modulated by the orientation of the attended stimulus. In the visible condition, the TAE magnitude was 5.00° ± 0.41° (attend same) versus 3.99° ± 0.45° (attend opposite) (two-tailed paired t test; $T(3) = 11.36$, $p < 0.01$), and in the invisible condition, it was 3.19° ± 0.17° versus 2.18° ± 0.45° (two-tailed paired t test; $T(3) = 3.49$, $p < 0.05$).

The TAE magnitude for the attention-target-absent condition fell between the two attentional conditions above. One possibility for this result is that feature-based attention to an opposite stimulus had suppressed the adaptation to the invisible adaptor. Another possibility is that the lack of the control of attention in this condition might have produced an unexpected effect. One critical issue is that the observers might have attended to the left visual field when there was no stimulus in the right visual field, whereas in other conditions, they were explicitly told to attend to the target in the right visual field. Although this condition presents an interesting result, further study is warranted for interpreting this result unambiguously.

The lack of attentional modulation in the spatial-attention experiments could come from the effects of the full-field Mondrian unrelated to visibility per se; first, the full-field Mondrian masks might have distracted the observers from attending to the target, and second, contrast normalization of the adaptors with the stronger mask stimuli could potentially contributed to the reduction of attentional effects. To address this issue, we have repeated the invisible condition of the feature-based-attention experiment by using full-field Mondrian masks (Figure S5A). To avoid the perceptual disappearances, we displayed the attention targets on both eyes, but otherwise, the experimental procedure was identical to the main experiment.

The results of this control experiment are shown in Figures S5B and S5C. As before, the TAE magnitude was larger when the target with the same orientation was attended (3.29° ± 0.15°) than when the target with the opposite orientation was attended (2.46° ± 0.36°; two-tailed paired t test, $T(3) = 3.83$, $p < 0.05$). This suggests that it is unlikely that the absence of attentional effects in the spatial-attention experiment comes from the more powerful attentional distraction caused by full-field Mondrian masks. Moreover, our replications of the feature-based-attention experiment in these two additional control experiments corroborate our main finding that the processing of invisible stimuli is modulated by feature-based attention.

Continuous Flash Suppression Reduces TAE Magnitude

In all experiments, we found reduction in TAE magnitudes in the CFS conditions. This contrasts with a previous finding that the TAE magnitude does not depend on the dominance duration in binocular rivalry [S7]. However, given the recent finding that CFS reduces even

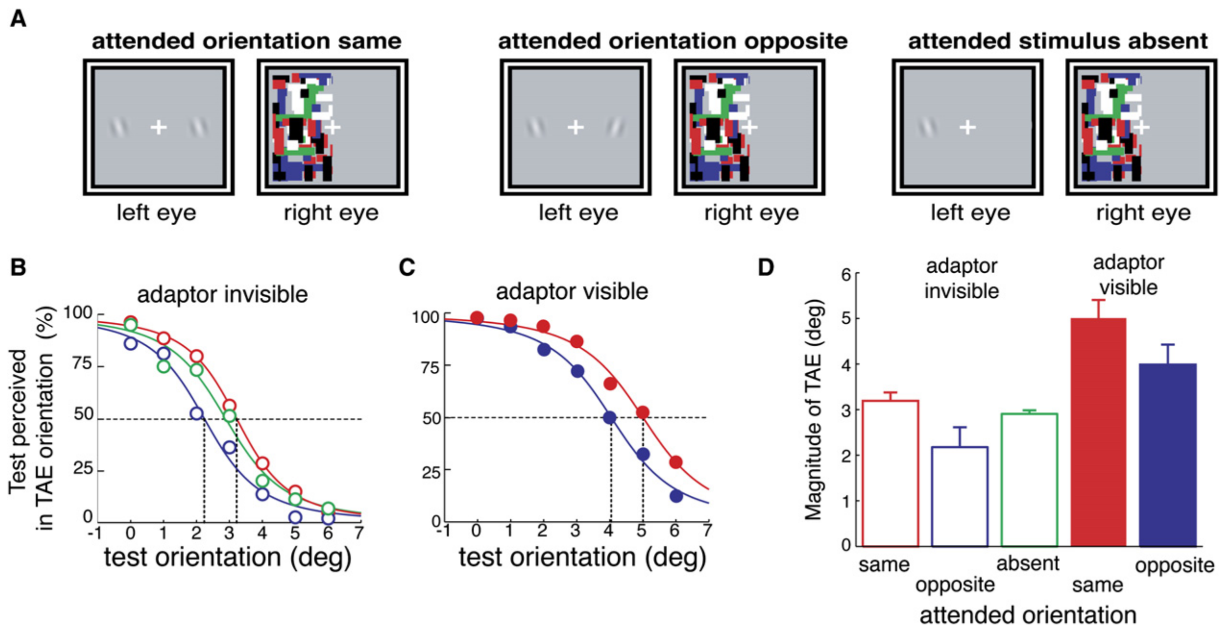

Figure S4. Feature-Based-Attention Experiment with a Single Attention Target

(A) Three stimulus conditions are illustrated: The visible Gabor on the right visual field had the same orientation as the invisible adaptor on the left visual field (*left*); the attention target had the opposite tilt orientation (*middle*); or the attention target is absent (*right*).

(B) The results of the adaptor-invisible condition. The percentage of trials in which observers reported a tilt in the direction of TAE is plotted against the orientation of the test stimulus. The open red circles indicate the results of the condition in which the target with the same tilt was attended, and the open blue circles indicate the condition in which the target with the opposite tilt was attended. The green circles indicate the results of the attention target-absent condition.

(C) The results of the adaptor-visible condition. The solid red circles and the solid blue circles indicate the results of the attend-same and attend-opposite conditions, respectively.

(D) Summary of the results. Error bars indicate one SEM.

the formation of afterimage, which is believed to occur at an earlier stage than the TAE [S6], it may not be all that surprising that CFS also reduced the TAE.

In fact, suppression is deeper in CFS (1.4 log-unit contrast threshold elevation) than in binocular rivalry (0.4 log-unit elevation) [S8]. The strong suppression by CFS may be responsible for the reduction of TAE.

Supplemental Experimental Procedures

Observers and Apparatus

Four observers including one of the authors (R.K.) participated in each experiment. Observer R.K. participated in all experiments, whereas the other three were different for each experiment. For each experiment, the same observers participated both in the main and associated control conditions. All had normal or corrected-to-normal vision. Stimuli were displayed on a γ-linearized CRT monitor (LaCie Electron 22 inch monitor) at a 75 Hz vertical refresh rate. The observers viewed the stimuli dichoptically through a mirror stereoscope.

Stimuli and Procedure

We used Gabor stimuli both for adaptation and test stimuli. The spatial frequency of the Gabor was 1.5 cpd, the sigma of the Gaussian envelope was 0.32°, and the Michelson contrast was 0.5. The Mondrian patterns consisted of rectangles with random sizes and random colors (red, green, blue, black, or white).

Before the adaptation experiments, baseline performance for orientation discrimination was obtained at the locations where TAE was to be measured later in each experiment (see below). The results of these baseline experiments were used for testing whether adaptation produced a significant TAE. In the adaptation experiments described below, a block began with 20 s of preadaptation, followed by a series of trials each consisting of 5 s top-up adaptation and a test. Both during the preadaptation and the top-up adaptation, the observers were instructed to maintain attention at the location given before the beginning of each block of trials. For the adaptor-invisible conditions, we kept the adaptors invisible throughout the preadaptation period as well as the top-up period.

Spatial-Attention Experiment

To induce the TAE, two adapting Gabors were presented to the left eye; one was on the left and the other was on the right of the fixation cross at an eccentricity of 2.0° of visual angle. The adaptors were tilted 15° to the left from the vertical. For the invisible conditions, the adaptors were rendered invisible by presentation of different Mondrian patterns every 67 ms (15 Hz) to the right eye. At the beginning of a block, there was 20 s of preadaptation, followed by a series of trials, each consisting of 5 s top-up adaptation and a test. Throughout a block, the observers were instructed to pay attention either to the left or the right spatial marker that was presented on top of the Mondrian pattern. The two spatial markers spatially overlapped with the positions of the adaptors. In the visible condition, the Mondrian patterns were absent, and the observers were instructed to attend to the left or right adaptor location. There were eight types of blocks (2 [attend-to-left and attend-to-right] × 2 [test-left and test-right] × 2 [adaptor visible and adaptor invisible]) and each block was repeated twice, resulting in a total of 16 blocks per observer. Test stimuli were presented either at the attended location or unattended location within the same block. In one block, ten samples were made per test orientation (70 trials per block). In total, each observer performed 1120 trials (70 trials × 16 blocks). The observers reported whether the test stimulus was tilted to the left or right by pressing a key. The test stimulus remained on the display until the key press. The data were sorted based on whether the test location was attended during adaptation or not and were collapsed across different test locations and attended locations.

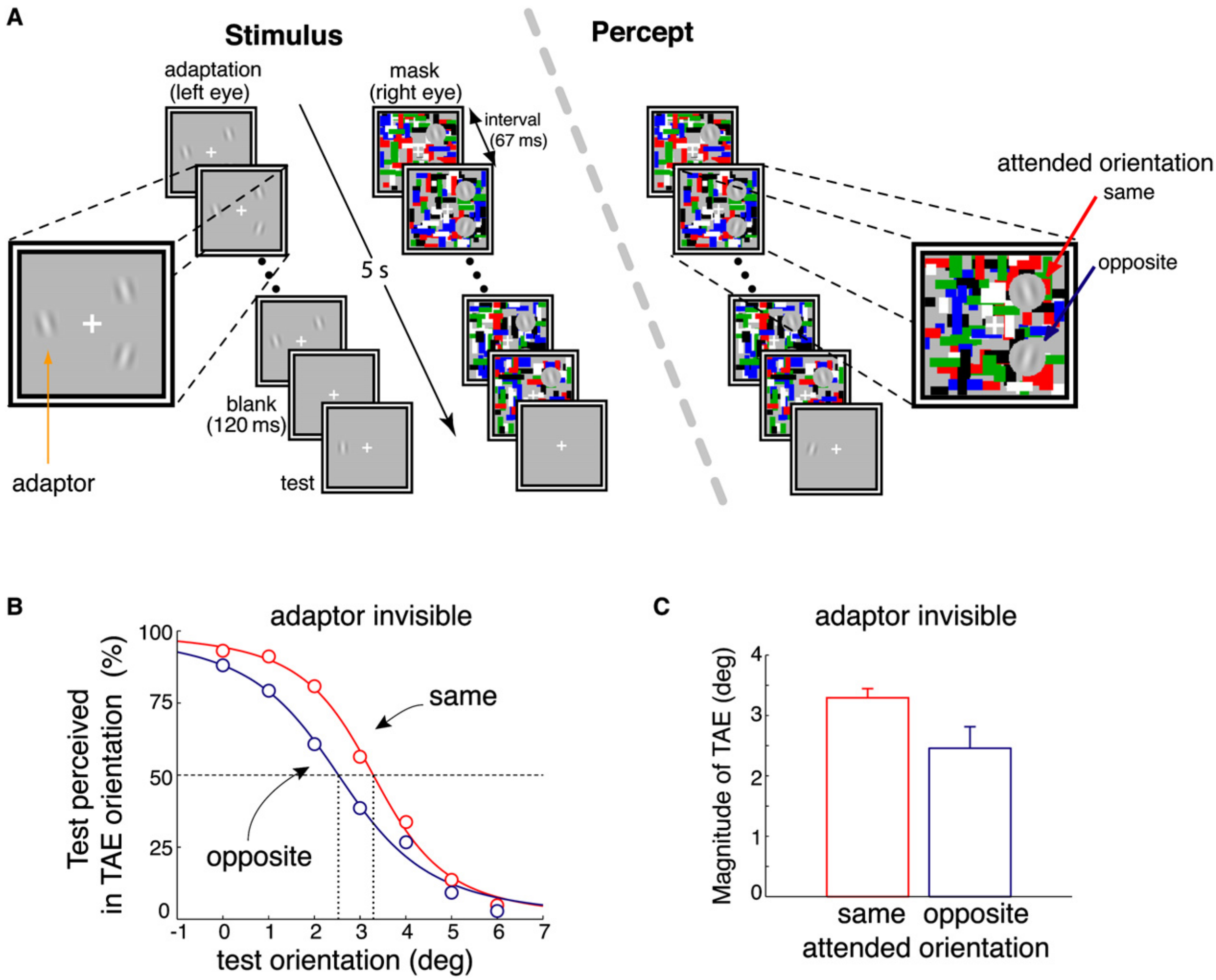

Figure S5. Stimuli and Results of the Feature-Based-Attention Experiment with Full-Field Mondrian Masks

(A) A schematic illustration of a typical trial.

(B) The pooled data across four observers is shown in the same manner as Figure 2.

(C) Summary of the results. Error bars indicate one SEM.

Feature-Based-Attention Experiment

One Gabor adaptor with a 15° tilt to the left from the vertical was presented to the left visual field of the left eye at an eccentricity of 2.0° from fixation. Two Gabors were presented as the attention targets to the right visual field of the left eye. One of the attention targets had the same tilt as the adapting Gabor (i.e., left-tilt), and the other target had an opposite tilt (right-tilt). In half of the sessions, the attention target at the top had the same tilt as the adaptor, and the target at the bottom had the opposite tilt. In the other half, this positional relation was reversed. Mondrian patterns were presented only to the left visual field of the right eye so that the adapting Gabor was subjectively invisible but the two attention targets remained visible. At the beginning of a block, there was 20 s of preadaptation, followed by a series of trials, each consisting of 5 s top-up adaptation and a test. Throughout a block, the observers were instructed to pay attention to one of the two attention targets. A test stimulus was always presented at the adapted location, that is, the left visual field of the left eye. Within a block, the orientations of the adaptor and the attention targets were fixed and were counterbalanced across blocks. Thus, there were eight types of experimental blocks (2 [attend-to-top and attend-to-bottom] × 2 [same-orientation-top and same-orientation-bottom] × 2 [adaptor visible and adaptor invisible]) and each block was repeated twice, resulting in a total of 16 blocks per observer. In order to exclude the possibility of transfer of TAE or shifts in the cognitive bias, we included the control experiment, in which the adaptor was physically absent behind the Mondrian pattern presented in the left visual field of the right eye (Figure S3): There were four such additional blocks (2 [attend-to-top and attend-to-bottom] × 2 [attend-to-left-tilt and attend-to-right-tilt]). These four adaptor-absent blocks were interleaved with eight blocks of the main experiments, which as a whole, repeated twice (24 blocks). Thus, in total, each observer performed 1680 trials (70 trials × 24 blocks). The data were sorted based on whether the attended target had the same or opposite tilt as the adaptor.

The observers were asked after each block whether they saw the suppressed Gabor stimuli during adaptation. The blocks in which they reported seeing an adapting Gabor, even slightly, during the adaptation period were discarded and repeated later. To minimize carryover effects of adaptation across blocks as well as to maintain the effect of CFS, we required the observers to take a rest (at least 5 min) between blocks.

For each experimental condition, a total of 40 samples were made per test orientation. We fitted a probit curve to the data of individual observer and estimated the TAE magnitude as the point of subjective equality where the curve intersected 50% response level. In the text, TAE magnitudes are represented as the mean magnitude ± the standard error across four observers.

Experiments in the Supplemental Data

Spatial-Attention Experiment with a Letter Task (1)

The stimuli and design were identical to the main spatial-attention experiment with a few modifications. The letter streams were used as dichoptic masks. Each letter was presented for 80 ms, and there was a 40 ms blank between successive letter presentations. On each stream, the letter "X" appeared three, four, or five times. The observers were asked to count the occurrences of "X" in the stream at the location to which the experimenter asked them to attend before each block of trials.

The target letters were evenly spaced in the letter streams so that the observers are encouraged to pay attention continuously throughout a trial. Three of the target letters were always presented at pre-fixed temporal positions with a small jitter; the three positions were the 7th, 21st, and 35th letter of the stream of 42 letters. The jitter was randomly shifting each original position by 0, +1, or −1. For the trials with four letters, an additional letter was presented either at the 14th or 28th position with the one-letter jitter. For the trials with five X's, all of these positions were used.

Because we were to exclude the trials in which observers failed to answer the number of "X," a larger number of samples (24 trials instead of 20 trials) were made per condition.

Spatial-Attention Experiment with a Letter Task (2)

Adapting stimuli were slowly moving Gabor patches tilted either to the right or to the left from the vertical. They were presented to the left eye for 5 s. The orientations of the adaptors were randomized across trials, and the two adaptors had the same orientation within a trial. Test stimuli were stationary Gabors with a variable orientation between -7° (left tilt) to 7° (right tilt) with a step size of 1°. They were presented either to the right or to the left of fixation. Letter streams identical to those used in the above experiment were presented to the right eye. There were a total of eight conditions (2 [tilt directions of adapting stimuli] × 2 [attention task locations] × 2 [test locations]).

At the end of each trial, the observers reported (1) the tilt direction (left or right) of the test stimulus presented for 120 ms, (2) the number of occurrences of the letter X at the indicated location, and (3) whether they saw the Gabor stimulus any time during adaptation. The trials in which the observers failed to answer the number of X's correctly or the trials in which the adapting stimulus was visible were discarded from the analysis. The CFS failed to suppress the adapting stimuli only in 1.7% of trials.

After every 50 trials, the observers took a break for a minimum of 5 min so that the CFS remained effective throughout the experiment. Twenty samples were made for each test condition, resulting in a total of 2400 trials (15 [test orientations] × 8 [conditions] × 20 [samples]).

The visible condition was identical except that no letter streams were presented. Instead of the letter task, the observers were instructed to count the number of small orientation changes, which could occur three, four, or five times at the location indicated by a white circle before each trial. The size of the orientation change was one degree and lasted for one frame (13 ms). After every 50 trials, observers took a rest of 5 min. Three responses were obtained after each trial: the orientation of the test stimulus, the number of orientation changes at the designated location, and the visibility of the suppressed adaptor. The data were processed in the same way as the main experiment. The order of the two experiments was counterbalanced across observers. The performance was comparable for the letter task (73.5% ± 4.0%) and for the orientation task (75.1% ± 4.6%; $T(3) = -0.477$, $p = 0.67$).

Manipulations of the Difficulty of Attending to Targets in Feature-Based Attention

In the control experiments described in Figure S4, the stimuli and procedure were identical to the main feature-based attention. In the experiment shown in Figure S5, we conducted only the adaptor-invisible condition. The radius of the protection zone for the attention targets was 0.8°.

Supplemental References

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