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# Attention-based long-lasting sensitization and suppression of colors

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ABSTRACT

In contrast to the short-duration and quick reversibility of attention, a long-term sensitization to color based on protracted attention in a visual search task was reported by Tseng, Gobell, and Sperling (2004). When subjects were trained for a few hours to search for a red object among colored distracters, sensitivity to red was increased for weeks. This sensitization was quantified using ambiguous motion displays containing isoluminant red–green and texture-contrast gratings, in which the perceived motion-direction depended both on the attended color and on the relative red–green saturation. Such long-term effects could result from either sensitization of the attended color, or suppression of unattended colors, or a combination of the two. Here we unconfound these effects by eliminating one of the paired colors of the motion display from the search task. The other paired color in the motion display can then be either a target or a distracter in the search task. Thereby, we separately measure the effect of attention on sensitizing the target color or suppressing distracter colors. The results indicate that only sensitization of the target color in the search task is statistically significant for the present experimental conditions. We conclude that selective attention to a color in our visual search task caused long-term sensitization to the attended color but not significant long-term suppression of the unattended color.


## 1. Introduction

We are concerned here with showing how the relative saliency of specific visual features, say motion or shape or color red compared to green, is not constant but depends on the statistics of attentional selection of these features, i.e., on their history of relevance (Gál et al., 2009; Libera & Chelazzi, 2009; Vidnyánszky & Sohn, 2005). Tseng, Gobell, and Sperling (2004) developed a tool to measure observers' internal salience changes induced by learning that involved attentional selection. They used a third-order chromatic motion paradigm introduced by Lu and Sperling (1995). Two colors (red and green) elicit motion in opposite directions in the motion display, and the direction of apparent motion (up or down) depends on the relative salience of the two colors. In Tseng et al. (2004), observers were trained in a search task in which a target letter appeared on squares of the to-be-attended color (either red or green) and other letters ("distracters") appeared on squares of the unattended color. Before they began practice in the search task, and again after they had reached a criterion level of performance, the subjects were tested in the third-order motion task. It was found that searching for red greatly increased the salience of red in the motion task, and that this increased salience persisted for over a month.

The long survival of the search-induced change in saliency demonstrates a sustained plasticity in the human visual system in response to an important feature in the environment. The question addressed in the present study is whether the attention-produced changes in sensitivity to a specific feature was the result of increased sensitivity for the attended feature, or decreased sensitivity for the systematically neglected one, or a combination of these two effects. It is known that the process of visual attentional selection involves both attentional facilitation of the selected stimuli and suppression of the task-irrelevant ones (Reynolds, Chelazzi, & Desimone, 1999; Reynolds & Desimone, 2003; Rizzolatti & Carmarda, 1987; Von Grunau, Bertone, & Pakneshan, 1998). However, whether attention-produced changes in the sensitivity to visual features are mediated by the facilitatory or the inhibitory mechanisms of attentional selection, or by both, is not known. The study by Tseng et al. (2004) was not designed to differentiate between these possibilities, and this missing information is critical in understanding the mechanisms of neural plasticity.

In Tseng et al. (2004), the two colors of the ambiguous motion display used to test the modulation of the relative saliencies of specific colors were both present in the search display: one

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matched the color that was attended during search and the other matched one of the distracter colors. Thus, the observed change in the relative saliency of these two colors could have been due either to the attention-produced increased sensitivity to the color that was attended during search or to decreased sensitivity to the distracter color or a combination of these two.

The current experiment is designed to isolate and specifically test the contribution of both sensitization and suppression in the adaptive modulation of color saliency. To this end, we made the following modifications to the paradigm used by Tseng et al. (2004). In the experiments reported here, the search and ambiguous motion display share only one color (red). Thus the unused color (green) in the motion paradigm is a neutral color because it is not directly accessed in the search. This allows us to observe the salience changes of the red color in two conditions: one that isolates the sensitization and another that isolates the suppression effects of attention.

## 2. Methods

### 2.1. Procedures

Observers were pre-tested and post-tested with the same third-order motion paradigm before and after the search task (Fig. 1). Prior to each motion test, both at the pre-training and post-training phases, individual calibration was conducted to ensure that the motion stimulus red/green gratings were indeed isoluminant. The search task always involved two colors, red and blue. During the search training stage, eight observers were assigned randomly to two groups of four, and each group underwent two phases of training. The two phases differed only in the target color of search. Observers in one group started the experiment with the condition that was designed to selectively test for color sensitization mediated by the facilitatory component of the attentional selection (*sensitization* condition); they searched for targets on red squares, never on blue. Then they were tested with a red-plus-green motion stimulus. Only the color red was shared between the search training stimuli and the motion test stimuli. Therefore, any change in salience is attributable to sensitization of red. The other four observers started the experiment with the condition that isolated desensitization mediated by the attentional suppression component (*suppression* condition); targets occurred only on blue squares, never on red. Then they were tested with a red-plus-green motion stimulus. Again, only the color red was shared between the search stimuli and the motion stimuli. Therefore, any change in salience is attributable to the attentional suppression of red.

### 2.2. The third-order ambiguous motion task

Psychometric functions for the motion discrimination task were obtained in a block of 400 trials with assay stimuli at ten red-to-green saturation ratios, |R|/|G|, that varied from 1/8 to 8. Observers reported whether the motion-direction was going up or down by pressing one of the two keys on the keyboard. Observer's response preference was plotted as a function of saturation ratios, and the psychometric function obtained before any search training took place was considered as baseline and compared with that obtained after search training.

Each trial (Fig. 2) was composed of five frames, each displayed for 60 ms, alternating between red/green sine-wave gratings (odd frames) and high-/low-contrast, half-black–half-white random noise textured square-wave gratings (even frames). The mean luminance of contrast-modulated gratings (both in high- and low-contrast regions) and saturation-modulated chromatic gratings was the same as the background luminance. Red/green sine-wave gratings were generated by modulating along the L-M (long-medium wavelength) cardinal axis in color space (Derrington, Krauskopf, & Lennie, 1984; Lu, Lesmes, & Sperling, 1999; MacLeod & Boynton, 1979), and were made isoluminant by a two-stage calibration process that represents an improvement over the Anstis and Cavanagh (1983) method to eliminate any residual luminance (Lu & Sperling, 2001). After removing unwanted luminance contaminations with strict calibration procedures, the stimuli would elicit no reliable responses from luminance-based (first-order) or texture-based (second-order) motion systems – any reliable behavioral responses have to be from the salience-based (third-order) motion system.

In the even frames, the high-contrast stripes have high salience because: (1) the high-contrast texture differs more from the neutral background than does the low-contrast texture and (2) the high-contrast stripes are only 1/3 as wide as the low-contrast stripes and therefore tend to appear as figure against a low-contrast background. In the odd frames, the salience of red or green stripes is jointly determined by two components: (1) A stimulus component that depends on the relative saturation of the two colors (this is varied from trial-to-trial). (2) A perceptual component, which is a function of the color's salience for the observer, and it

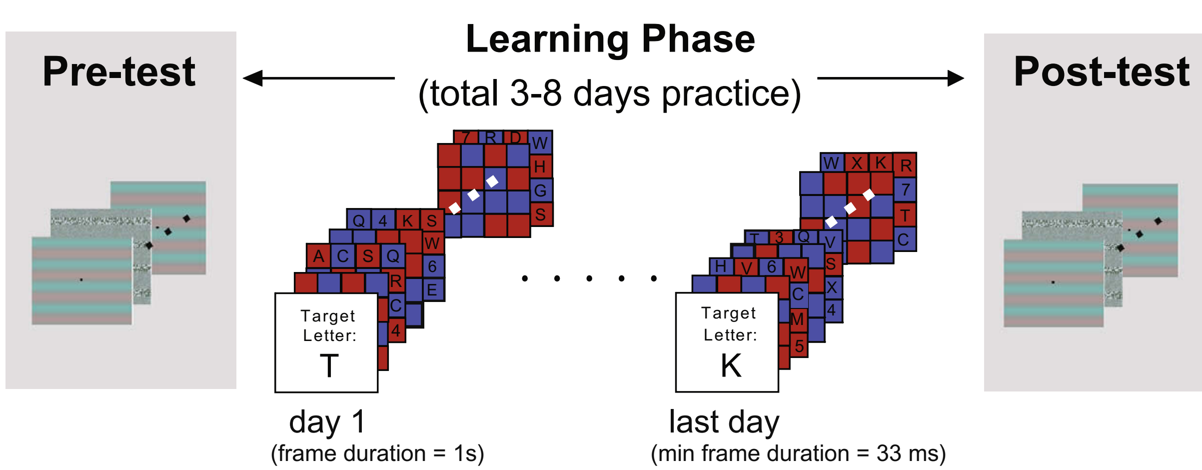


**Fig. 1.** Experiment procedures. The third-order ambiguous motion task was conducted without any attentional instruction before and after each of the two 3–8 days learning phases. In a learning phase, observers searched for target letter embedded either on red or on blue colors; the target color was randomly assigned at the beginning of each learning phase. The difficulty of search task was increased by reducing the search frame duration, beginning with 1 s per search frame to minimum 33 ms per frame.

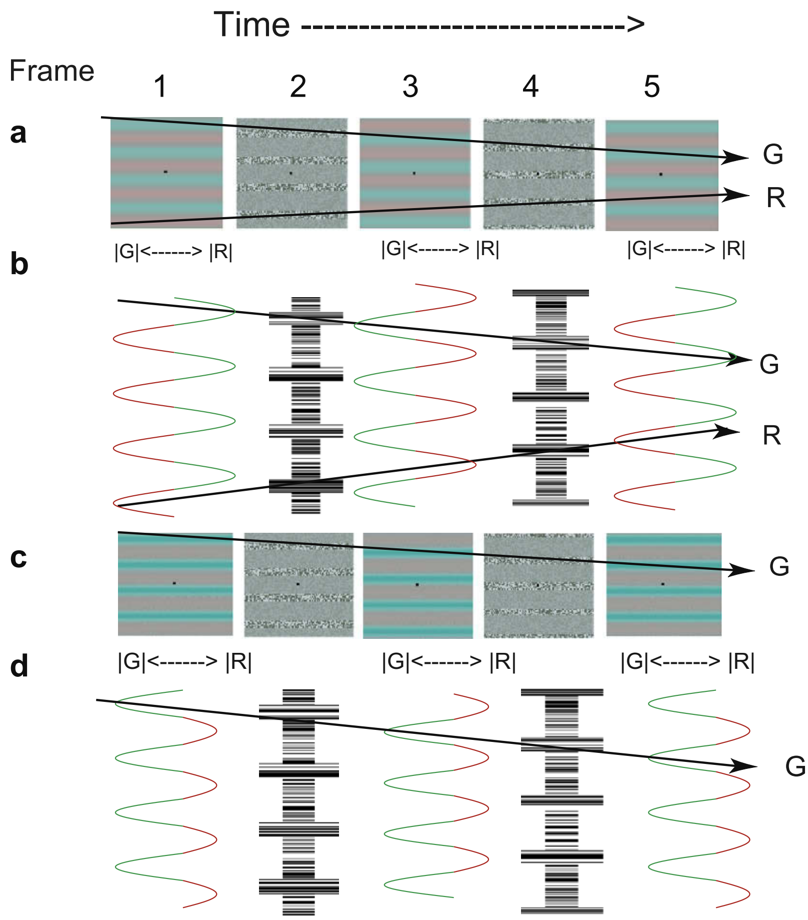


**Fig. 2.** A third-order chromatic motion display for measuring the relative salience of two colors. (a) The visual display consists of five superimposed frames, each 60 ms in duration. Frames 1, 3, 5 are isoluminant red–green sinusoidal gratings. Frames 2, 4 are composed of alternating stripes of high- and low-contrast isoluminant textures. (b) Saturation and contrast of the component frames. The high-contrast stripes have high salience. However, the direction of apparent motion is completely ambiguous. If on a given trial the red (or green) stripes happen to be perceived as more salient, the red (green) areas of high salience in frames 1, 3, 5 will correlate with the high-contrast areas in frames 2, 4, and the third-order motion system will signal upward (downward) motion. When red and green stripes are equally salient, no consistent directional motion is perceived. (c) A green is more salient example: green stripes have eight times the saturation of red stripes, therefore, the areas occupied by green stripes are perceived as more salient than red areas, as shown schematically in (d). Consequently, observers tend to perceive downward motion.

may depend on the observer's attentional state, among other factors. Successive frames had a 90-deg phase shift so that the direction of apparent motion was ambiguous (Fig. 2a), depending on whether red or green had higher salience. Observers perceive unambiguous motion in the third-order motion paradigm of Fig. 2 only if the red and green components in the odd frames are not equally salient. For example, if green is more salient, then observers perceive the direction consistent with the motion path along green and high-contrast-texture patches (Fig. 2c and d).

### *2.3. The search task*

Observers monitored a stream of 4 × 4 arrays of alphanumeric characters shown on red or blue colored background and reported the location ($x$, $y$) if a target letter was detected on the target color (Fig. 3). A target color, either red or blue, was decided for each observer throughout each phase of search training (Fig. 3a and b). A target letter, varied across trials, was randomly selected among a set of five letters (E, G, K, R, Y) and displayed at the beginning of the trial. Table 1 lists all used alphanumeric stimuli used in our experiment. The observer's task, after noticing the target letter in the initial frame, is to first press a space bar to start the trial and, at the end of each trial, to report either the location of the target letter by pressing one of 16 keys arranged in a 4 × 4 matrix on the keyboard, or to report that no target occurred on that trial, by pressing the space bar. There was no upper limit on response time, and feedback was given on each trial. The target letter was regarded as a distracter (foil) when shown on the non-target color (Fig. 3d). The response for target present was considered correct if the target location itself or one of its nearest four adjacent locations (up, down, left, right) were indicated. Half of the trials contained the target letter in the target color, half did not.

A 4 × 4 "color-only" pre-cueing display of the same duration as the search array, i.e., an array of colored squares without letters was presented immediately prior to each search array to aid observers' performance (Fig. 3c). At the slow presentation rates of the earliest training trials, this gives the impression of letters emerging on the colored squares. At the rapid presentation speeds achieved by practiced observers, the pre-cue display is not noticeable as a separate event. The spatial arrangement of colors in each trial was changed randomly 10 times within each trial, and in each unique search array, the spatial configuration of colors of the pre-cueing display was exactly the same as the search frame displayed 33–1000 ms later with the letters and numbers (Fig. 3d). The color-only display gave observers a cue for the distribution of colors. In-so-far as observers could promptly distribute their attention to the locations of target colors in the pre-cueing frames, they could reduce their search area by a factor of 2. Thereby, in the process of

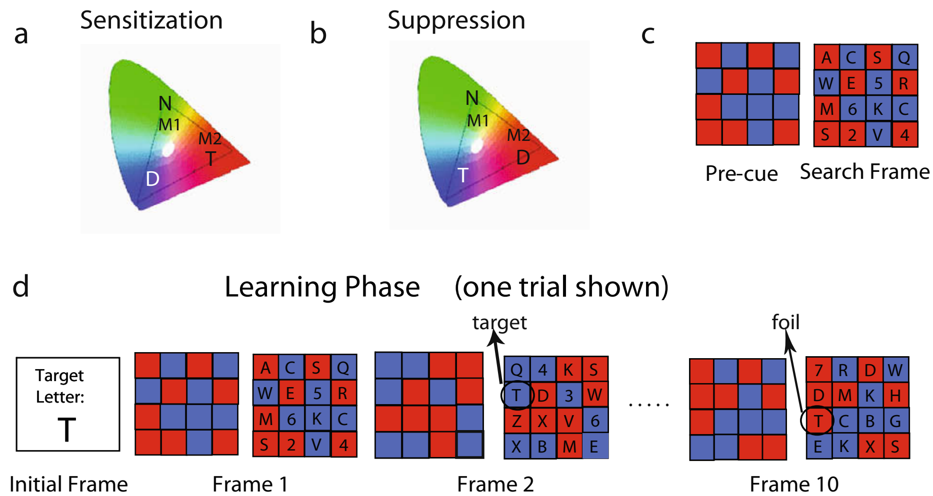


**Fig. 3.** Stimuli used in the search task and motion task to measure facilitation and suppression. (a, b) The positions of the letters only very approximately indicate their representations in CIE *x*, *y* color space: targets (T), distracters (D), neutral color (N); M1 and M2 represent the maximally saturated green and red stripes that could occur in the isoluminant chromatic gratings of the motion-direction task. The interior of the triangle indicates the range of colors that could be produced on the display monitor. (c) A pre-cue display indicating the color distribution that is presented prior to each search frame. The spatial color arrangement changed 10 times within each trial. The color distribution in the pre-cue frame is identical to that of the actual search frame, and it gives observers a spatial cue for the distribution of attention. (d) Experimental procedure for the suppression condition (blue target), Search arrays are composed of distracters, foils, and possibly a target. The target appears on the target color (blue here) on just one of the 10 search arrays and only on half the trials. Foils (target letters on the unattended color, red here) and distracters (21 non-target letters plus six numbers) fill the remaining locations.

**Table 1**
Alphanumeric stimuli for the search task. At the start of each trial, a randomly selected letter from the Target Letter Set was shown to the subject and it became the target for that trial. Only half the trials include a frame containing the target letter appearing on an attended color square. The selected target letter on an unattended color is a foil. Seventeen letters and six numbers served as distracters. All individual non-targets (one foil, four potential foils, 23 distracters) have the same probability of being selected to fill the remaining unattended background squares. This generates an expected number of 2.9 false targets (foils) per trial.

| | |
|---|---|
| Possible target set (5) | E, G, K, R, Y |
| Distracter letters (17) and numbers (6) | C, D, F, H, J, L, M, N, P, Q, S, T, U, V, W, X, Z, 2, 3, 5, 6, 7, 9 |
| Possible false targets (foils) | E, G, K, R, Y |

attending to the spatial distribution of color in order to optimize their search, observers were potentially sensitized to the target color, and de-sensitized to the non-target color.

The duration of each search frame was 1000 ms (60 frames) in the beginning, and was shortened as the observer's performance improved. The rule for shortening the duration was to have nine correct reports in the most recent 10 trials. Shortening of the frame duration was continued until the observer failed to advance to a higher level in 100 trials. After the first phase of the experiment was concluded with the post search motion test, there was a period of 3–5 days to permit the results of the search training to subside. Then, in phase two, the target color for both groups was switched and the subjects underwent a second complete test-training-test cycle.

As the subject's performance improved with practice, the sequence was speeded up so that the entire sequence of 10 arrays took only one second or less. Therefore, although the subjects had 3–8 h practice sessions, the actual accumulated time spent viewing the displays never exceeded about one hour (average search rate of 10 frames/s $\times$ 10 frames yields an average trial duration of one sec, and the total number of trials was 3000).

### 2.4. Stimuli and apparatus

The motion stimuli measured 10 cm $\times$ 10 cm at a viewing distance of 60 cm (spatial frequency = 0.43 cpd); temporal frequency = 4.17 Hz; mean luminance = 22 cd/m$^2$. All motion displays were shown on an Apple 1710 multisync color monitor (refresh rate = 67 Hz) controlled by a 10-bit Radius Thunder 1600/30 graphic card in a 7500/100 Power PC Macintosh running Matlab programs based on the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997).

The visual search task array was 12 deg $\times$ 12 deg at a viewing distance of 90 cm. The size of each square was about 3 deg; hence the center-to-center distance between adjacent letters was about 3 deg. The fixation point was a central square subtending 0.3 deg $\times$ 0.3 deg. The visual search stimuli were displayed on another CRT color monitor (model VL500) with a refresh rate of 60 Hz in another experiment room. Observers did not know these two tasks administered in different rooms on different days were relevant, nor that they would be requested to have a post-test after visual search training.

## 3. Results

### 3.1. Search task

It took 3–8 h sessions (average was 5.0 sessions) for an observer to reach an approximate asymptotic performance level in the visual search task of phase 1. The minimum frame duration our observers achieved was 33 ms (two refreshes), i.e., a rate of 15 new search frames per second (a color-only pre-cue frame preceded each new search frame). In phase 2, observers achieved an equivalent performance to phase 1 in 4.1 sessions on the average.

### 3.2. Motion task

Observers' responses in the third-order ambiguous motion task are plotted as proportions of trials in which motion was seen in the direction favored by the red color as a function of red/green saturation ratio. The psychometric function before search was taken as the baseline (Figs. 3 and 4a and b, black lines). The lateral shift between the baseline and post-search-training psychometric function indicate attention-produced salience changes. A leftward horizontal shift of the post-training psychometric function indicates that, after search, red now behaves in the motion task as though it was more saturated, that is, more salient. A rightward shift of the post-training psychometric function indicates red has become less salient.

### 3.3. Measuring the amount of sensitization and suppression

We determine the lateral shift $\Delta r$ (on a log_base2 scale) between pre- and post-search-training psychometric functions that minimizes the sum of squared differences between the two functions; details are given in Appendix A. A leftward shift is positive, and indicates an increase in salience of red relative to green (in the motion test). The lateral shift between pre- and post-psychometric functions when the target color was red (sensitization condition) is the amount of sensitization, called sensitization for short. When the color of the squares where targets never occurred (the background) was red (suppression condition), the pre- to post-training psychometric function shift is called suppression. Rightward shifts represent negative shifts on the log scale and indicate a decrease in the relative salience of red.

### 3.4. Sensitization versus suppression

Fig. 6 summarizes the obtained values for sensitization and suppression for the eight subjects and for their average. The values are in terms of the training-induced change in saturation ratio $(\text{red}/\text{green}) = 2^\wedge(-\Delta r*)$ where the symbol "∧" signifies exponentiation. For example, the average value of sensitization for the eight subjects was 1.40, indicating that searching for red targets made red stripes in the ambiguous motion post-test stimulus behave as though they had 1.40 times more saturation than they did prior to search training ($t(7) = 3.1$, $p < 0.009$). On the other hand, the average suppression is 0.94, which is a non-significant suppression of the salience of red after ignoring red while searching for blue targets ($t(7) = -0.93$, $p < 0.192$).

### 3.5. Effectiveness of the search task

While we cannot say whether the search task in the experiment was more effective than other tasks might have been in altering salience, we can say that it was effective for all subjects in altering salience in the expected direction. That is, in Fig. 5 the data for all subjects lie above the line of slope 1, the locus of points for which suppression equals sensitization. Because of the significance of the lines $x = 1$ and $y = 1$ in Fig. 5 (no suppression and no sensitization, respectively), we use these lines as axes for referring to quadrants in what follows. Ideally, we would expect all points to lie in the upper left quadrant, i.e., suppression $x < 1$ and sensitization $y > 1$; this is the case for four observers. For the upper right quadrant, data for two observers indicate that both search tasks caused an increase in the relative salience of red, i.e., they both produced sensitization. In both cases the expected sensitization following red-target search was greater than the unexpected sensitization following blue-target search, so a net positive effect of search training was weakly present. For the lower left quadrant, one observer's red-target search task produced an unexpected decrease in sensitization but it was not as much as the expected decrease in the salience of red produced by suppression, i.e., by training to ignore red. Finally, for one observer, the red-target search task produced sensitization but the blue-target task had no effect whatever on suppression. Thus, for all subjects, the net effect (including sensiti-

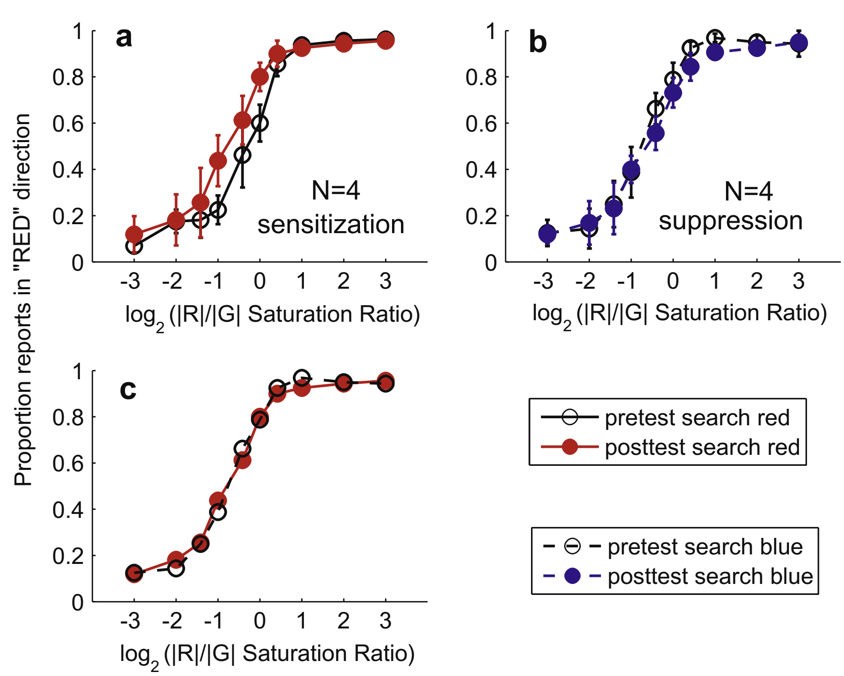


**Fig. 4.** Group psychometric curves representing motion-direction judgments before and after (a) search training in sensitization conditions (red), followed by (b) search training in suppression conditions (blue). The abscissa is $\log_2$(saturation(red)/saturation(green)) in the motion-direction task; the ordinate is the proportion of motion-direction judgments in the "red" direction. The black lines represent pre-training baseline curves. (c) The post-training curve from phase 1 training and the pre-training curve of phase 2 effectively coincide, indicating that the effect of learning from phase 1 completely survived the 3–5 days break between the two phases of training. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

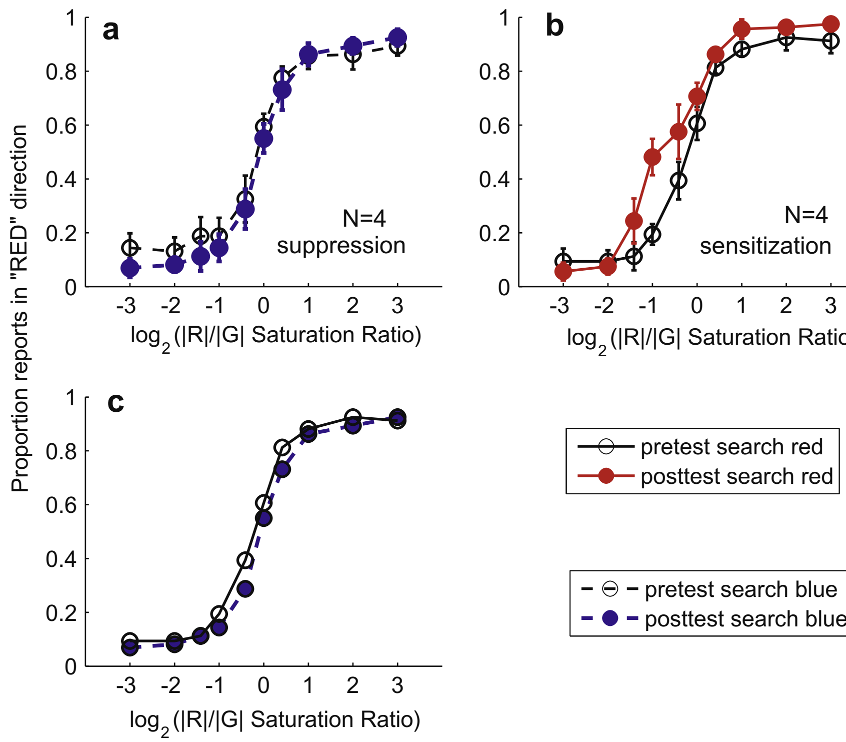


**Fig. 5.** Group psychometric curves representing motion-direction judgments before and after (a) search training in suppression conditions (blue) followed by (b) search training in sensitization conditions (red). (c) The post-training curve from phase 1 training and the pre-training curve of phase 2 effectively coincide, as in Fig. 4. See Fig. 4 for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

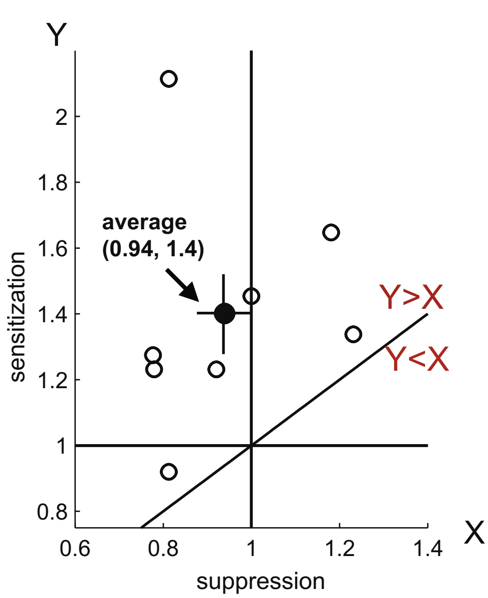


**Fig. 6.** Results summary: sensitization versus suppression for eight observers. The abscissa $X$ is the experimentally determined amount of change (suppression) in the red/green color saturation ratio (red/green $= 2^\wedge(-\Delta r*)$) in the motion task produced by search training in the suppression paradigm; the ordinate $Y$ is the change (sensitization) in red relative to green in the motion task $2^\wedge(-\Delta r*)$) produced by search training in the sensitization paradigm. For all observers, the net effect of the two training procedures (sensitization, suppression) produced the expected net result $Y > X$ (points fall above the black line of slope 1). The greater the distance of a point above the line of slope 1, the greater is the net effect (in the expected direction) of the search training procedures on color salience. The filled black circle represents the average data of all eight subjects, showing a large amount of sensitization and an insignificant amount of suppression. Bars indicate standard errors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

zation and suppression conditions) of the search task on salience was in the expected overall direction.

### 3.6. Sensitization greater than suppression

We have already noted that, on average, the increase in the salience of red, the attended color produced by searching for red targets, is significantly larger than the decrease in the salience of red produced by searching for blue target and being forced to ignore red distracters and foils. This observation of greater sensitization effect was also confirmed by a within-subject t test on the values of $2^\wedge(-\Delta r*) =$ saturation ratio (red/green) of all observers obtained in the two training conditions ($t(7)$=3.4098, $p < 0.006$). Examination of Fig. 5 shows that this is also true for each individual subject: For all subjects, the magnitude of the change produced by the sensitization search was greater than the magnitude of the change produced by the suppression search.

Taken together, we find that practice on a visual search task that requires selective attention to a specific color results in a large long-term increase in the sensitivity to this color. There is also a trend suggesting a possible suppression to the color that is to be ignored during the search but this effect is not statistically significant.

## 4. Discussion

Recently, it has been shown that a few hours of practice in a search task during which one specific color of the search display is selectively attended while the other distracter colors present in the display are neglected, leads to long-lasting changes in the relative saliency of the two colors (Tseng et al., 2004). The present results provide evidence that such attention-produced modulation of feature sensitivities is due mainly to an increase in the sensitivity to the color that was attended during the search task, with no statistically significant effect on the sensitivity to the neglected color. Our results, obviously, do not address the question of whether attention-produced sensitization and suppression (on occasions, if any, when it occurs) might be independent, separate processes.

Mere exposure to the stimuli cannot explain the different outcomes in the suppression and sensitization conditions of the experiment because the observers saw similar stimuli in both conditions. The targets in sensitization conditions are false targets (foils) in suppression conditions. What differentiates sensitization and suppression is the attentional state of the observer during the time of observation. Similarly, as commented by an anonymous reviewer, these results cannot be explained by simple reinforcement models of perceptual learning.

The dissection of attentional facilitation of the task-relevant, selectively attended stimuli, from the simultaneous attentional suppression of the task-irrelevant, to-be-neglected stimuli has often been attempted. There is psychophysical (Cheal & Chastain, 2002; von Grunau et al., 1998) and neurophysiological (Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998; O'Craven, Rosen, Kwong, Treisman, & Savoy, 1997; Slotnick, Hopfinger, Klein, & Sutter, 2002; Slotnick, Schwarzbach, & Yatins, 2003) evidence that the facilitatory and inhibitory components of attentional selection may affect visual processing separately. Both ERP responses (components: P1 and N1) (Luck, Woodman, & Vogel, 2000; Valdes-Sosa et al., 1998) and neural activity in motion-specific visual cortical areas MT and MST (Treue & Trujillo, 1999) are suppressed for the unattended motion vector when attention is directed to a motion signal of a different direction. Brain imaging studies have found that when attention is directed to a motion vector, the areas selective for the attended feature result in increased neuronal activity (Beauchamp, Cox, & DeYoe, 1997; Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; O'Craven et al., 1997; Saenz, Buracas, & Boynton, 2002; Saenz, Buracas, & Boynton, 2003). Similar findings of feature-selective rise of neuronal activity are also noted from single-unit recording in the monkey (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993; Haenny, Maunsell, & Schiller, 1988; Haenny & Schiller, 1988; Maunsell, Sclar, Nealey, & DePriest, 1991; Motter 1994a, 1994b; Treue & Martínez-Trujillo, 1999). Our methodology was designed to separate attention-produced sensitization and suppression components; the results point to a much larger role of sensitization.

The saliency of a visual feature is determined both by its physical parameters (in a bottom-up way) and by its actual behavioral relevance (in a top-down way). There is a large body of evidence that prior experience, including adaptation and visual learning, can strongly affect the bottom-up saliency of a given feature or stimulus (Hepler, 1968; Masland, 1969; McCollough, 1965, 2000; Webster & Mollon, 1991). However, it is only recently that research on the plasticity of attentional functions started to reveal the role of prior experience in the top-down component of saliency computation (Hahn, Ross, & Stein, 2006; Egner et al., 2008).

The results obtained here suggest that, in addition to the well-known continuous recalibration of visual processing according to the statistics of the physical properties of the visual input (Seitz & Dinse, 2007; Seitz & Watanabe, 2005), there is a simultaneous attention-based top-down recalibration of visual feature saliencies according to the statistics of the attentional selection of a given feature, i.e., its behavioral relevance. The recalibration consists of increased salience of the attended feature with no significant change in the salience of the unattended feature.

## Appendix A

The usual way to compare pre- and post-psychometric performances is to fit both curves to a well-known function (such as a normal cumulative distribution function) and determine the horizontal shift between them from the parameters of the fitted functions. Because our data cannot be readily fitted to a common function, we adopt a purely empirical approach that makes no assumption about the shape of the cumulative distribution function. The independent variable is the log of the contrast ratio, r, the saturation ratio between red and green in the motion stimuli:

$$r = \log\_\text{base}\_2(\text{saturation (red)}/\text{saturation(green)})$$

Conceptually, we shift horizontally the post-test psychometric function with respect to the pre-test psychometric function to see what is the shift that produces the best fit. Our empirical approach encounters problems of unmatched tails when shifting the psychometric curves, because our empirical data have finite domains of $r$, $-3 \leqslant r \leqslant 3$. To solve this problem, we used a normalization factor to introduce a cost for reducing the area of overlap between psychometric curves due to the horizontal shift, as follows:

We define $r_d$ as the set of $r$ values for which data were obtained. Let $r_{min}$ and $r_{max}$ be the members with the smallest and largest value of $r$ in $r_d$; in or case $r_{min} = -3$ and $r_{max} = 3$. We constructed two functions: the pre-test baseline $B(r)$ psychometric function and the post-test experimental psychometric function $E(r)$ by linearly interpolating among the ten data points to obtain a continuous function between $r_{min}$ and $r_{max}$. We used a total of 101 values for each of $B(r)$ and $E(r)$ between, and including, $r_{min}$ and $r_{max}$.

Let $\Delta r$ be the horizontal shift produced by the post-test experimental manipulation.

$$\text{Let } r1 = \max(r_{min}, r_{min} + \Delta r)$$
$$r2 = \min(r_{max}, r_{max} + \Delta r)$$

We estimate $\Delta r^*$, the value of $\Delta r$ that minimizes

$$\sum_{r=r1}^{r2} \text{CostFn} * (E(r) - B(r - \Delta r))^2$$

where CostFn = $(r_{max} - r_{min} + |\Delta r|)/(r2 - r1)$, i.e., the ratio of the total range to the overlap range of $r$, is a normalization factor that introduces a cost for reducing the area of overlap between $B(r)$ and $E(r)$.

The value $\Delta r^*$ is a direct measure of the horizontal shift of the psychometric function after training manipulation. If $\Delta r^*$ is positive, it indicates that the psychometric curve shifts to the left and red color is more salient after training; negative $\Delta r^*$ indicates the opposite, i.e., less salient red after training. If the training is not effective in altering the salience of red relative to green, $\Delta r^*$ should be close to zero.

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