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Research Article

Voluntary Attention Enhances Contrast Appearance

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ABSTRACT—***Voluntary (endogenous, sustained) covert spatial attention selects relevant sensory information for prioritized processing. The behavioral and neural consequences of such selection have been extensively documented, but its phenomenology has received little empirical investigation. We asked whether voluntary attention affects the subjective appearance of contrast—a fundamental dimension of visual perception. We used a demanding rapid serial visual presentation (RSVP) task to direct endogenous attention to a given location and measured perceived contrast at the attended and unattended locations. Attention increased perceived contrast of suprathreshold stimuli and also improved performance on a concurrent orientation discrimination task at the cued location. We ruled out response bias as an alternative account of the pattern of results. Thus, this study establishes that voluntary attention enhances perceived contrast. This phenomenological consequence links behavioral and neurophysiological studies on the effects of attention.***

Human sensory systems have a limited information processing capacity. For example, the visual world normally contains much more information than one can process at a given time. Visual attention helps people to overcome this limitation by selecting certain aspects of the scene for prioritized processing. Attention improves behavioral performance in a variety of tasks (reviewed in Carrasco, 2006) and enhances the neural processing of sensory stimuli (reviewed in Reynolds & Chelazzi, 2004). Although these effects are well established, the effect of voluntary attention on subjective appearance is still a matter of debate. In this study, we asked: Does paying attention to a location affect how the object at that location looks?

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This question has been debated since the beginning of experimental psychology and physiology. Whereas Fechner believed that attention does not alter sensory impressions, James (1890/1983) and Helmholtz (1866) claimed that attention intensifies sensory impressions. Empirical evidence regarding voluntary attention and appearance has been scarce and mixed: The finding that attention reduces perceived brightness contrast (Tsal, Shalev, Zakay, & Lubow, 1994) was disputed by a report that attention reduced response variability without changing brightness perception (Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). Another study reported that attention increased brightness of overlapping transparent surfaces (Tse, 2005). However, it is not clear whether this effect is attributable to the perceptual grouping mechanism for multiple surfaces or to a general mechanism of attention. Thus, the question remains as to whether attention can change the appearance of a single, isolated stimulus; in the study reported here, we investigated the effect of voluntary attention on perceived contrast.

Covert attention refers to attention that is deployed to a location in the absence of eye movements. There are two types of covert attention (e.g., Muller & Rabbitt, 1989; Nakayama & Mackeben, 1989): First, voluntary attention refers to the controlled allocation of processing resources. Voluntary attention is endogenous (goal driven), takes approximately 300 ms to be deployed, and can be sustained. Second, involuntary attention refers to the automatic orienting to salient objects and events in the environment. Involuntary attention is exogenous (stimulus driven) and transient (its effect peaks at ~100 ms and decays rapidly). These two modes of attention can have differential effects on performance, as shown by studies on the contrast response function (Ling & Carrasco, 2006; Lu & Dosher, 2000), temporal-order judgments (Hein, Rolke, & Ulrich, 2006), texture segmentation (Yeshurun, Montagna, & Carrasco, 2008), and cue-validity effects in visual search (Giordano, McElree, & Carrasco, 2004).

Recently, we (Carrasco, Ling, & Read, 2004) developed a protocol to evaluate the effects of involuntary (exogenous, transient) attention on subjective appearance. The key to this procedure is to ask observers to make a discrimination contingent on a comparative judgment. Observers were instructed to "report the orientation of the stimulus that is higher/lower in contrast." Thus, they were asked not to directly compare two stimuli on the dimension of interest (contrast), but rather to give a separate judgment (orientation) contingent on the comparison of interest. The rationale for adopting this procedure is twofold: It minimizes bias by emphasizing the contingent judgment while "disguising" the comparative judgment to reduce its importance and demand characteristics; in addition, it allows for the concurrent assessment of attentional effects on performance and appearance.

Using this procedure, our own and other research groups have demonstrated that involuntary attention affects appearance on a number of perceptual dimensions. Involuntary attention affects perceived contrast (Carrasco, Fuller, & Ling, 2008; Carrasco et al., 2004; Fuller, Rodriguez, & Carrasco, 2008; Ling & Carrasco, 2007), spatial frequency and gap size (Gobell & Carrasco, 2005), color saturation (Fuller & Carrasco, 2006), motion coherence (Liu, Fuller, & Carrasco, 2006), flicker rate (Montagna & Carrasco, 2006), speed (Turatto, Vescovi, & Valsecchi, 2007), and size of a moving object (Anton-Erxleben, Henrich, & Treue, 2007).

The study we report here focused on voluntary attention. This type of attention has been widely investigated in behavioral and physiological studies. However, whether voluntary attention affects the appearance of contrast has not been established. Ostensibly, the finding that involuntary, exogenous attention increases perceived contrast (Carrasco et al., 2004) is consistent with neurophysiological and neuroimaging evidence that voluntary, endogenous attention increases sensory gain in early visual areas (Brefczynski & DeYoe, 1999; Gandhi, Heeger, & Boynton, 1999; Martinez-Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000). Indeed, such concordance has been interpreted as a phenomenological correlate of the physiological findings (Treue, 2004). However, this linkage is based on studies of different types of attention and hence remains indirect.

We sought to clarify the link between the phenomenology and the behavioral and neural mechanisms of attention by assessing the effect of voluntary, endogenous attention on perceived contrast. Such a link is of particular interest given that the original opinions of Fechner and James were concerned with voluntary attention and appearance, and also because previous research has yielded discrepant findings regarding the effects of endogenous attention on perceived brightness (Prinzmetal et al., 1997; Tsal et al., 1994; Tse, 2005). To investigate the effect of voluntary attention on perceived contrast, we used the paradigm from our previous study (Carrasco et al., 2004) in conjunction with a rapid serial visual presentation (RSVP) task to direct voluntary covert spatial attention.

METHOD

Participants

Nine undergraduate and graduate students participated as observers. Four were experienced psychophysical observers. All but 2 observers (authors) were naive to the purpose of the experiment. All participants had normal or corrected-to-normal vision. The experimental procedures were approved by the institutional review board at New York University, and all participants gave informed consent.

Apparatus

The stimuli were generated using Matlab (MathWorks, Natick, MA) and custom code and were displayed on a 21-in. CRT monitor (1024 × 768 pixels at 100 Hz). The display was calibrated using a Photo Research (Chatsworth, CA) PR650 SpectraColorimeter to linearize the gamma. Observers' eye position was monitored using an infrared video camera system (ISCAN, Burlington, MA). Videos of the left eye were recorded and inspected later to detect breaks from fixation. All observers were able to maintain steady fixation, breaking fixation in less than 1% of trials.

Stimuli

There were four types of displays in the experiment (see Fig. 1): fixation, cue, RSVP, and Gabor patches (sinusoidal gratings in a Gaussian window). The background of the screen was gray (53 cd/m^2), and a centrally located cross (0.5° × 0.5°, 100 cd/m^2) served as the fixation point. The cue was denoted by the thickening of part (peripheral cue) or all (neutral cue) of the horizontal bar of the fixation cross. The RSVP display consisted of two streams of letters (distractors: *N*, *R*, *Z*, *B*, *A*, *M*, *L*, and *T*; target: *X*) located at 6° eccentricity (0.8° azimuth). The letters were white (106 cd/m^2) and about 0.6° in size. Each RSVP stream lasted for 1.2 s and consisted of from five to eight letters (adjusted for each observer so that detection accuracy remained about 85%). The Gabor patches (4 cycles/deg, *SD* of the Gaussian window = 0.3°) were located on the horizontal meridian and centered at 6° of eccentricity, with a small orientation offset from vertical (±3–10°; adjusted for each observer so that discrimination accuracy remained about 85–90%). Observers viewed the displays from a distance of 57 cm, with their heads stabilized by a chin rest.

Procedure

Figure 1 shows a sample trial. After a period of fixation, the cue appeared for 400 ms, followed by the presentation of two RSVP streams for 1.2 s. The RSVP streams were followed by a 100-ms interstimulus interval (ISI), after which two Gabor patches appeared simultaneously for 40 ms. One of the Gabors was the standard (32% contrast), and the other was the test, which had

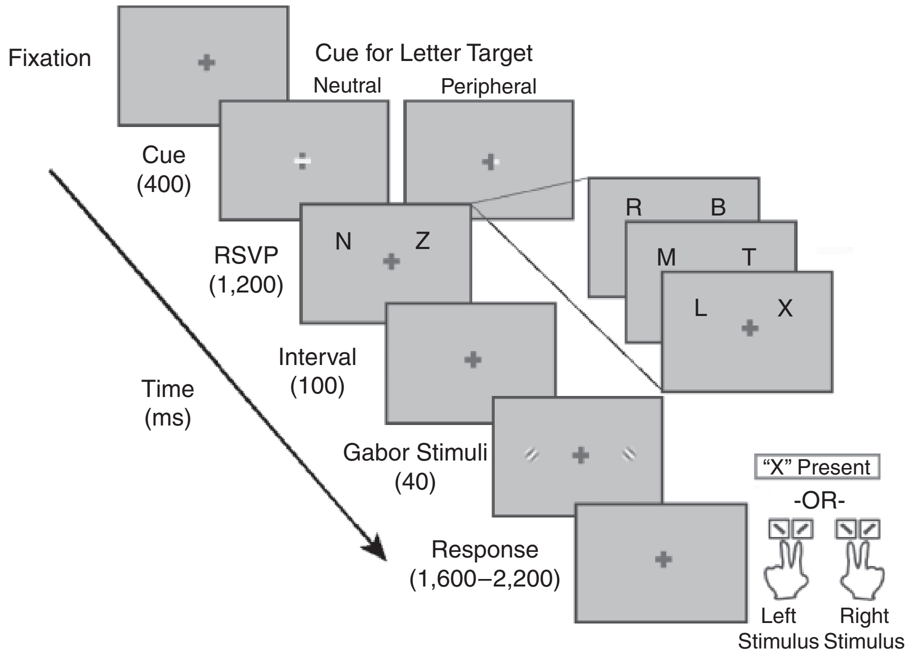

Fig. 1. Schematic depiction of the trial sequence. For ease of illustration, the cues are depicted as a brightening of all or part of the horizontal bar of the fixation cross, whereas in the experiment, the cues were presented as a thickening of all or part of this bar. Also for illustrative purposes, the tilt of the Gabors is exaggerated, and only four rapid serial visual presentation (RSVP) frames are shown. The inset depicts the response scheme: If an *X* was present in the RSVP stream, participants pressed the space bar; otherwise, they reported the orientation of the Gabor stimulus with the higher contrast, using the right hand if it was the Gabor on the right and the left hand if it was the Gabor on the left. For either hand, one of two possible keys was pressed to indicate whether the Gabor tilted to the left ("\") or to the right ("/").

one of nine contrast levels (13%, 20%, 25%, 29%, 32%, 35%, 40%, 50%, and 76%). The test contrast levels were equiprobable.

We used an RSVP detection task to engage focal attention at a location. Observers were told to attend either to the cued RSVP stream (peripheral cue) or to both streams (neutral cue) and to detect the presence of a target letter (*X*). They were told that if they detected the *X*, they should press the space bar and ignore the subsequent Gabor patches. The neutral cue appeared on half the trials, and the peripheral cue appeared on the other half. The target letter was present on only 20% of the trials (and was equally likely in the left and right locations). On peripherally cued trials, the target letter could appear only on the cued side. Each observer's RSVP rate was determined during practice trials so that initial accuracy of performance was around 85%. During the experiment, observers' performance was monitored on-line, and the RSVP rate was adjusted dynamically to ensure that accuracy remained about 85%.

Observers were informed that the target was rare and were told not to respond to the target's absence. They were instructed that when they did not see the target letter, they should instead report the orientation of the higher-contrast Gabor (i.e., the appearance judgment). If the left Gabor was of higher contrast, observers were to press the "z" key to indicate it had a counterclockwise tilt and the "x" key to indicate it had a clockwise tilt; if the right Gabor was of higher contrast, they were to use the numeric keypad and press the "1" key to indicate it had a counterclockwise tilt and the "2" key to indicate it had a clockwise tilt. Thus, with a single key response, observers indicated both the location and the orientation of the higher-contrast stimulus, so the key press provided a measure of both their appearance judgment and their discrimination performance. Observers were required to respond within the time allotted by a variable response window (1.6–2.2 s). The tilt of the Gabors was determined individually in a practice run before the experiment such that orientation discrimination performance was around 85 to 90%. Once determined, the amount of tilt was fixed throughout the experiment for a given observer.

Cue, orientation of the Gabors, and locations of the test and standard stimuli were randomized on every trial. Furthermore, observers were explicitly informed that the cue carried information only about the RSVP task, and not about the orientation-contrast task. Observers completed 1,080 trials in 12 blocks of 90 trials separated by breaks.

The rationale for using the demanding RSVP task in combination with a high-validity peripheral cue was to encourage observers to endogenously attend to the cued location. The short ISI (100 ms) between the offset of the RSVP streams and the

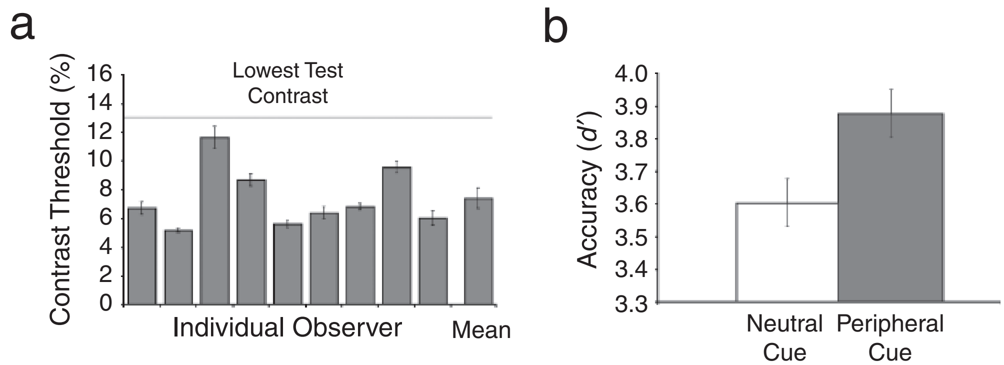

Fig. 2. Detection thresholds (a) and rapid serial visual presentation (RSVP) performance in the neutral- and peripheral-cue conditions (b). Individual observers' detection thresholds are shown, along with the group average. The horizontal line highlights the lowest contrast used in the test stimuli. Error bars represent standard errors of the means across six measurements for individual thresholds and across 9 observers for the average threshold. RSVP performance is reported in d' units, combined for the main and control conditions. Error bars are within-subjects standard errors of the means, calculated using the method of Loftus and Masson (1994).

Gabors ensured that sustained attention was likely still directed to the peripheral location when the Gabors appeared.

In addition to the main condition just described, observers completed a control condition. The only difference in the control condition was that when observers did not detect the target letter, they reported the orientation of the lower-contrast Gabor, rather than the orientation of the higher-contrast Gabor. The order of the main and control conditions was counterbalanced across observers. Had the results been driven by response bias (i.e., had observers tended to choose the Gabor in the cued location), then the control and main conditions should have yielded opposite patterns of results.

Detection Threshold

To ensure that all Gabor stimuli were visible to all observers, we measured individual observers' detection thresholds before they participated in the study. The trials for this assessment were identical to those in the main condition (Fig. 1) except that no cue was shown before the RSVP streams and a response cue (a thickening of the horizontal arm of the fixation point) was shown for 400 ms at the offset of the Gabor display. The Gabors were independently and randomly oriented horizontally or vertically, and observers were instructed to report the orientation of the Gabor indicated by the response cue. We varied the contrast of the Gabors in a 1-up 2-down staircase (Levitt, 1971) to measure the threshold of an orthogonal discrimination, which serves as a proxy for detection threshold (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Thomas & Gille, 1979). The staircase was run for 50 trials, and each observer completed a total of six staircases. After obtaining each observer's detection threshold, we set the contrast range of the Gabor stimuli in the appearance task such that the lowest contrast was higher than the thresholds of all the observers, thus ensuring that all Gabor stimuli were visible.

RESULTS

Detection Threshold

Threshold for making the orthogonal orientation discrimination was defined as the contrast level needed to obtain 71% correct performance. Figure 2a shows the individual thresholds; all were below the contrast of the lowest-contrast stimulus in the main and control conditions (13%). The average detection threshold was 7.4% (SD = 2.1%) contrast, significantly below 13%, $t(8) = 7.90$, $p_{rep} = .99$. These results demonstrate that all the Gabor stimuli in the main and control conditions were well above detection threshold (i.e., highly visible), ruling out uncertainty as a possible contributor to the observed effects of attention on appearance. It has been suggested that in the case of involuntary attention and targets of low visibility, observers may bias their response toward the cued location, and that the cuing effect may be due to a cue bias (Prinzmetal, Long, & Leonhardt, 2008). However, the effect of involuntary attention on appearance has been shown repeatedly with suprathreshold stimuli (Carrasco et al., 2004, 2008; Fuller et al., 2008; Ling & Carrasco, 2007).

RSVP Detection

We used the RSVP task to induce a focused state of attention to the cued location. Although performance on this task is not of main interest here, we present the data to show that attention was indeed effectively manipulated. Figure 2b shows average d' values in the neutral- and peripheral-cue conditions (combined for the main and control conditions, for which d' values were similar). Detection performance was significantly better for the peripheral-cue than for the neutral-cue condition (paired t test), $t(8) = 3.75$, $p_{rep} = .98$, $d = 0.50$. Analyzing the main and control conditions separately gave essentially the same outcome. Thus, the RSVP task effectively manipulated observers' selective attention.

Appearance in the Main Condition

Psychometric functions for contrast appearance were fitted with a four-parameter Weibull function: $\psi = \gamma + (1 - \gamma - \lambda)\left(1 - \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right]\right)$, where ψ is the proportion of response, x is the contrast, α is the location parameter, β is the slope, and γ and λ are lower and upper asymptotes, respectively. Fits were performed using maximum likelihood estimation, and goodness of fit was evaluated with deviance scores, which were calculated as the log-likelihood ratio between a fully saturated, zero-residual model and the data model. A score above the critical chi-square value indicated a significant deviation between the fit and the data (Wichmann & Hill, 2001).

Figure 3a shows the group-averaged psychometric functions and their Weibull fits. The ordinate is the percentage of trials on which observers chose the test stimulus to be of higher contrast than the standard stimulus, and the abscissa is the physical contrast of the test stimulus. Compared with the function for the neutral condition, the function for trials on which the test stimulus was cued is shifted to the left, indicating that observers were more likely to choose the test as being of higher contrast when it was cued than when it was not cued; the shift is in the reverse direction for trials on which the standard was cued. The three curves represent significant fits to the data, as all of the deviance scores were below the critical chi-square value, $\chi^2(9, 0.95) = 16.92$.

Another way to illustrate the effect is through shifts in the point of subjective equality (PSE). For this analysis, we fitted individual observers' data and derived PSEs for the test stimulus in the three cuing conditions (all individual deviance scores were also below the critical chi-square value); Figure 3b presents the group-averaged PSEs. As expected, the average PSE for the neutral condition was approximately 32%, the contrast of the standard stimulus. Cuing the test stimulus led to a lower PSE, whereas cuing the standard stimulus led to a higher PSE. This pattern of results indicates that cuing a stimulus increased its perceived contrast. A one-way analysis of variance (ANOVA) showed a significant effect of cuing, $F(2, 16) = 18.92$, $p_{\text{rep}} = .99$, $\eta_p^2 = .70$, and post hoc comparisons showed significant differences between the test-cued and neutral conditions, $t(8) = 2.61$, $p_{\text{rep}} = .98$, $d = 1.33$, and between the standard-cued and neutral conditions, $t(8) = 7.19$, $p_{\text{rep}} = .99$, $d = 2.22$. Figure 3c shows the distribution of individual PSEs in the test-cued and standard-cued conditions as a function of PSEs in the neutral condition. All the standard-cued PSEs were higher than the neutral PSEs (points fall above the unity line), and all but one test-cued PSE were lower than the neutral PSEs (points fall below the unity line). Thus, the effect of attention on perceived contrast was highly consistent across observers.

Appearance in the Control Condition

Our instructions emphasized the orientation discrimination task, rather than the comparative contrast judgment, and hence should have reduced potential response biases. To further rule out response bias as a possible cause of the differential PSEs induced by the cues, we included the control condition, in which observers reported the orientation of the lower- rather than the higher-contrast Gabor. If observers were simply picking the stimulus in the cued location, we would expect the pattern of results in this control condition to be the opposite of the pattern of results in the main condition; that is, observers would have reported the cued stimulus to be of reduced contrast. Contrary to this prediction, the pattern of results (the relative direction of shifts in the psychometric functions) was the same as in the main condition. The three psychometric functions in Figure 3d all represent fits with deviance values below the critical chi-square value. The PSE shift was similar to that found in the main condition (Fig. 3e). An ANOVA showed that cuing had a significant effect on PSEs, $F(2, 16) = 21.02$, $p_{\text{rep}} = .99$, $\eta_p^2 = .72$, and paired comparisons indicated that the test-cued PSE was smaller than the neutral PSE, $t(8) = 4.03$, $p_{\text{rep}} = .98$, $d = 1.79$, which in turn was smaller than the standard-cued PSE, $t(8) = 3.98$, $p_{\text{rep}} = .98$, $d = 1.69$. Figure 3f shows the distribution of individual PSEs, again displaying a consistent pattern of results across observers.

Orientation Discrimination

The orientation discrimination task was contingent on the appearance judgment. Here we report the discrimination performance when observers chose the standard (32% contrast) stimulus because this allows us to compare performance on the same physical stimulus in three cuing conditions: when the location of the standard stimulus was cued (cued condition), when the opposite location (the location of the test stimulus) was cued (uncued condition), and when neither location was cued (neutral condition; e.g., Fuller & Carrasco, 2006; Ling & Carrasco, 2007). Figure 4 presents averaged discrimination accuracy in the main and control conditions. Overall accuracy was high; performance was higher for the cued than for the uncued condition. A two-way repeated measures ANOVA revealed a significant main effect of cuing, $F(2, 16) = 5.82$, $p_{\text{rep}} = .96$, $\eta_p^2 = .42$. Neither the main effect of condition (main vs. control), $F(1, 8) = 1.47$, $p_{\text{rep}} = .79$, $\eta_p^2 = .16$, nor its interaction with cuing, $F(2, 16) < 1$, was significant. Thus, orientation discrimination was lower at the uncued location than at the cued location or at a neutral location regardless of the direction of the comparative judgment (i.e., whether observers chose higher- or lower-contrast Gabors).

We also analyzed response times (RTs) for the orientation judgment when observers selected the standard stimulus. We used median RTs for this analysis because RT distributions were positively skewed. A two-way repeated measures ANOVA re-

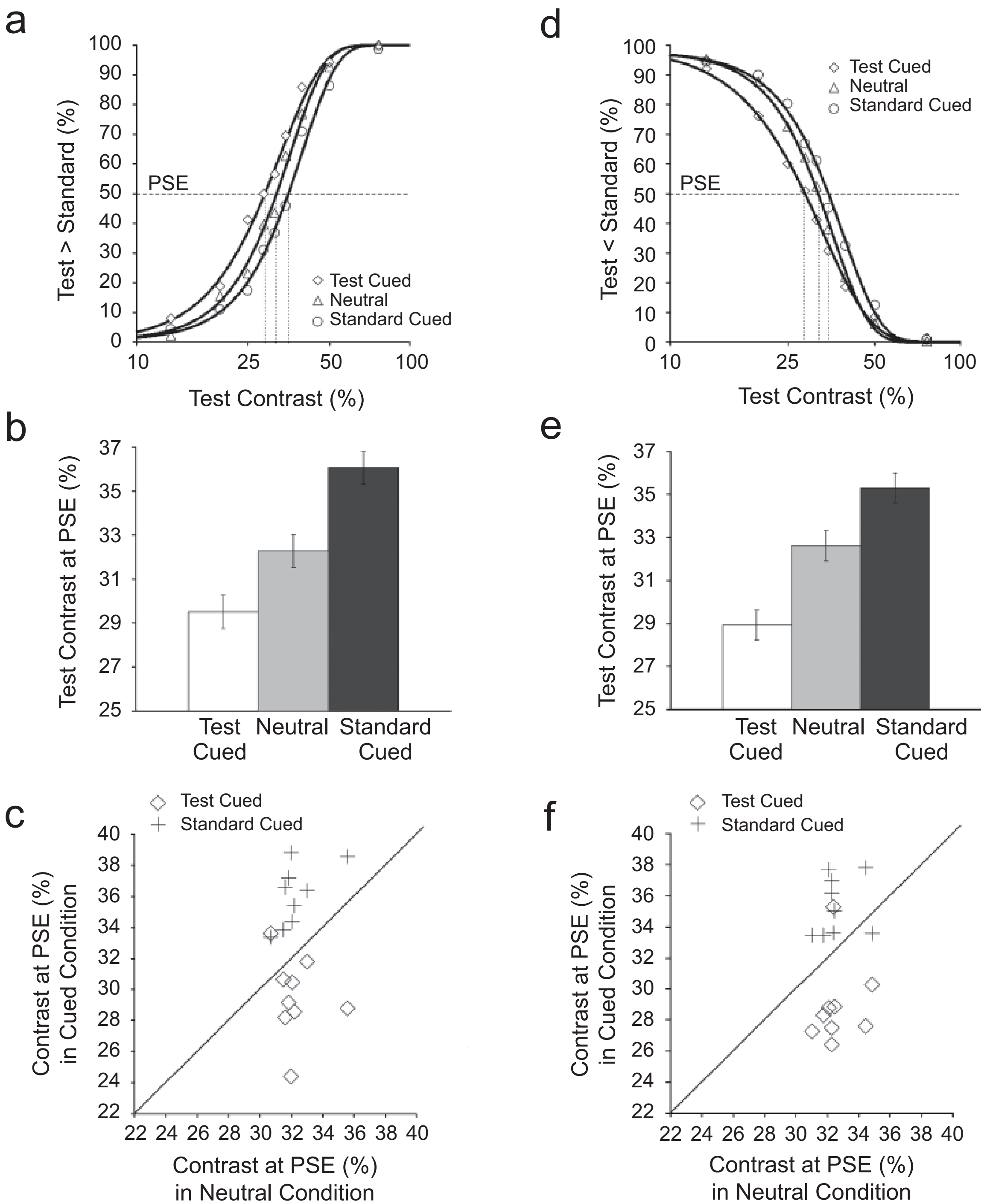

Fig. 3. Results for the contrast judgments. The top row presents psychometric functions for the main (a) and control (d) conditions. The graphs show the percentage of trials on which observers chose the test stimulus to be of higher (main condition) or lower (control condition) contrast than the standard stimulus, as a function of the physical contrast of the test stimulus. The middle row presents the values of the point of subjective equality (PSE) for the test stimulus for each of the three cue types in the main (b) and control (e) conditions. Error bars are standard errors of the means, calculated using the method of Loftus and Masson (1994). The bottom row presents scatter plots of individual observers' PSEs in the main (c) and control (f) conditions; each observer's PSEs for test stimuli in the test-cued and standard-cued conditions are plotted as a function of that observer's PSE for the test stimuli in the neutral-cue condition.

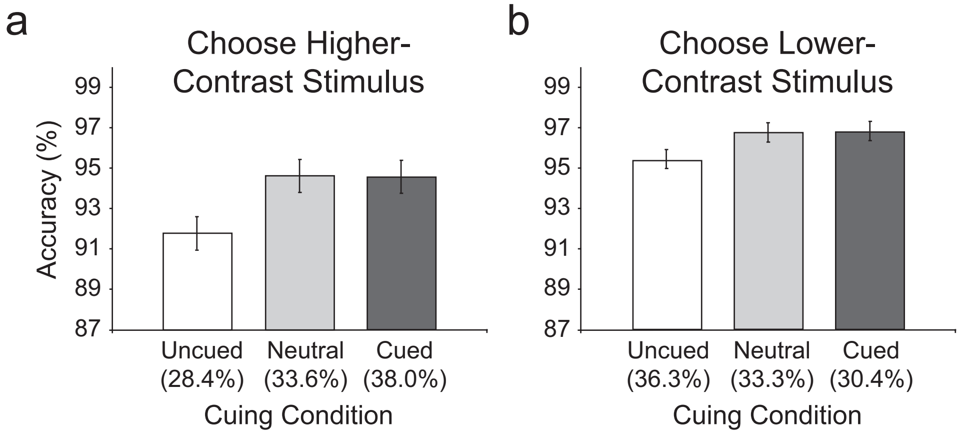

Fig. 4. Orientation discrimination performance (percentage accuracy) for trials on which observers chose the standard stimulus. Performance in the (a) main and (b) control conditions is graphed as a function of cuing condition: cued (i.e., standard cued), uncued (i.e., test cued), or neutral (i.e., neither stimulus cued). Error bars represent standard errors of the means, calculated using the method of Loftus and Masson (1994). The percentage of trials on which observers selected the standard stimulus in each condition is indicated.

vealed a significant main effect of cuing (Greenhouse-Geisser corrected), $F(1.31, 10.50) = 11.65$, $p_{rep} = .98$, $\eta_p^2 = .59$. The mean of the median RTs (collapsed across the main and control conditions) was 666 ms in the cued condition, 652 ms in the neutral condition, and 699 ms in the uncued condition. Neither the main effect of condition (main vs. control), $F(1, 8) = 2.74$, $p_{rep} = .86$, $\eta_p^2 = .26$, nor its interaction with cuing (Greenhouse-Geisser corrected), $F(1.58, 12.63) = 2.79$, $p_{rep} = .87$, $\eta_p^2 = .26$, was significant. Thus, attention facilitated RT, but reversing the instruction did not affect overall RT.

DISCUSSION

Does voluntarily attending to an object alter its appearance? Our results indicate that the answer to this age-old question is "yes." In the main condition, attending covertly to a peripheral location made a cued 29%-contrast stimulus and an uncued 36%-contrast stimulus both subjectively equivalent to a 32%-contrast stimulus (see the PSEs in Fig. 3b). The effect had a similar magnitude in the control condition and was highly consistent across observers in both conditions.

By combining an RSVP task with our appearance paradigm (Carrasco et al., 2004), we have developed a new method for studying the effects of voluntary attention on perception. An important feature of this method is that the task that engages spatial attention is independent from the appearance task. Voluntary attention is manipulated without giving observers information about the task of interest, so the role of possible cue-related strategies in task performance is limited. This renders the results comparable to those of studies on involuntary attention, as the cuing procedure contains no information regarding the perceptual discrimination.

This study shows that voluntary (endogenous, sustained) attention alters appearance. This result is consistent with studies revealing that exogenous, transient attention alters appearance on a number of perceptual dimensions (Carrasco, in press). It is intriguing that the increase in apparent contrast observed with voluntary attention parallels results found with involuntary attention (Carrasco et al., 2004, 2008; Fuller et al., 2008; Ling & Carrasco, 2007). Voluntary and involuntary attention have different time courses and control processes, as well as different effects on perceptual performance (see the introduction for a review). It is not obvious why two such different forms of attention would have similar phenomenological consequences. This finding invites exploration of other domains in which voluntary attention may alter appearance, and suggests that there may be some common mechanisms for prioritizing processing in early visual cortex.

In appearance studies, it is critical to control for response bias that can potentially influence participants' judgments. In the control condition, we reversed the direction of judgment by instruction (i.e., observers were told to choose the lower-contrast stimulus). If observers had simply chosen the stimulus on the attended side more often than the stimulus on the unattended side, this should have led to a reduction in apparent contrast. Instead, observers chose the stimulus on the attended side less often than the stimulus on the unattended side. This pattern reflects an increase in apparent contrast and is the same result as in the main condition. Reversing the instructions has been a successful control in many studies of the effects of involuntary (exogenous, transient) attention on appearance (Anton-Erxleben et al., 2007; Carrasco et al., 2004; Fuller & Carrasco, 2006; Fuller et al., 2008; Gobell & Carrasco, 2005; Ling & Carrasco, 2007; Montagna & Carrasco, 2006; Turatto et al., 2007). In addition, attention improved orientation discrimination in both the main and the control conditions. This finding is also inconsistent with a bias explanation, as response bias should not improve task performance. Finally, if observers had simply been biased to report the cued stimulus but reversed their response at the decision stage in the control condition, the overall RTs should have been longer in the control than in the main condition, a result we did not observe.

In studies of attention and appearance, it is also critical to evaluate the efficacy of the attentional manipulation. In this study, we had two such measures: detection performance on the RSVP task and orientation discrimination performance (which was contingent upon the appearance judgment). In both cases, performance was better for the attended than for the unattended stimulus. Thus, we can be certain that observers were attending as instructed. An independent measure of attention is vital; for instance, when exogenous attention altered the appearance of saturation but did not alter the appearance of hue, it was essential to show that the cue improved orientation discrimination performance in both cases, so that it was possible to interpret a null result (Fuller & Carrasco, 2006).

Previous work has yielded inconsistent findings with respect to the effects of voluntary attention on brightness (Prinzmetal et al., 1997; Tsal et al., 1994; Tse, 2005). As has been noted before, studies of brightness and studies of contrast might not yield the same results (Ling & Carrasco, 2007; Tsal et al., 1994). Indeed, luminance and contrast processing are largely independent for natural images, as are the mechanisms of luminance gain control and contrast gain control in the early visual system (Mante, Frazor, Bonin, Geisler, & Carandini, 2005). In brightness studies, the stimulus is generally a uniform surface against a background with a different luminance. A decrease in overall brightness could nevertheless lead to an increase in contrast (Schneider, 2006), complicating interpretation of the results. Studies on brightness are further complicated by the fact that one needs to consider both when the stimulus is brighter than the background and when it is darker than the background, as different results could emerge in these two cases (Prinzmetal et al., 1997). By using Gabor patches, which have been widely used to characterize the psychophysical and physiological mechanisms of early vision (Graham, 1989), we were better able to relate the effects of attention on perceived contrast to the extant psychophysical and physiological literature on attention and contrast sensitivity (for reviews, see Carrasco, 2006; Reynolds & Chelazzi, 2004).

Our findings provide evidence in support of Treue's (2004) claim that changes in appearance due to attention are the behavioral consequence of the neural mechanisms underlying preferential processing. This idea has been advanced as a "linking hypothesis" stating that the increased neuronal firing due to attention is interpreted as if the attended stimulus is of higher contrast (Reynolds & Chelazzi, 2004; Treue, 2004). This notion of sensory gain has been supported by evidence from neurophysiology (e.g., Martinez-Trujillo & Treue, 2002; Reynolds et al., 2000), psychophysics (e.g., Carrasco et al., 2000; Lu & Dosher, 2000), and neuroimaging (e.g., Brefczynski & DeYoe, 1999; Gandhi et al., 1999; Liu, Pestilli, & Carrasco, 2005). Our findings provide direct behavioral support for this hypothesis, as we manipulated voluntary attention (as in previous physiological studies). However, previous psychophysical studies concerning appearance have focused on involuntary attention (for a review, see Carrasco, in press).

To conclude, our results showed that voluntary attention increased perceived contrast, supporting James's (1890/1983) intuition more than a century ago. This effect was obtained for highly visible stimuli and cannot be attributed to response bias, as the control condition indicated. These results provide a phenomenological correlate of the effect of voluntary attention on perception, thus linking behavioral, neurophysiological, and neuroimaging studies of attention.

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REFERENCES

Anton-Erxleben, K., Henrich, C., & Treue, S. (2007). Attention changes perceived size of moving visual patterns. *Journal of Vision*, *7*(11), Article 5. Retrieved June 2008 from http://www.journalofvision.org/7/11/5/

Brefczynski, J.A., & DeYoe, E.A. (1999). A physiological correlate of the 'spotlight' of visual attention. *Nature Neuroscience*, *2*, 370–374.

Carrasco, M. (2006). Covert attention increases contrast sensitivity: Psychophysical, neurophysiological, and neuroimaging studies. In S. Martinez-Conde, S.L. Macknik, L.M. Martinez, J.M. Alonso, & P.U. Tse (Eds.), *Visual perception* (pp. 33–70). Amsterdam: Elsevier.

Carrasco, M. (in press). Visual attention alters appearance: Psychophysical studies of subjective experience. In T. Bayne, A. Cleeremans, & P. Wilken (Eds.), *Oxford companion to consciousness*. Oxford, England: Oxford University Press.

Carrasco, M., Fuller, S., & Ling, S. (2008). Transient attention does increase perceived contrast of suprathreshold stimuli: A reply to Prinzmetal, Long and Leonhardt (2008). *Perception & Psychophysics*, *70*, 1151–1164.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience*, *7*, 308–313.

Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: Support for signal enhancement. *Vision Research*, *40*, 1203–1215.

Fuller, S., & Carrasco, M. (2006). Exogenous attention and color perception: Performance and appearance of saturation and hue. *Vision Research*, *46*, 4032–4047.

Fuller, S., Rodriguez, R.Z., & Carrasco, M. (2008). Apparent contrast differs across the vertical meridian: Visual and attentional factors. *Journal of Vision*, *8*(1), Article 16. Available from http://www.journalofvision.org/8/1/16/

Gandhi, S.P., Heeger, D.J., & Boynton, G.M. (1999). Spatial attention affects brain activity in human primary visual cortex. *Proceedings of the National Academy of Sciences, USA*, *96*, 3314–3319.

Giordano, A.M., McElree, B., & Carrasco, M. (2004). On the automaticity and flexibility of covert attention. *Journal of Vision*, *4*(8), Abstract 627. Available from http://www.journalofvision.org/4/8/627

Gobell, J., & Carrasco, M. (2005). Attention alters the appearance of spatial frequency and gap size. *Psychological Science*, *16*, 644–651.

Graham, N.V. (1989). *Visual pattern analyzers*. New York: Oxford University Press.

Hein, E., Rolke, B., & Ulrich, R. (2006). Visual attention and temporal discrimination: Differential effects of automatic and voluntary cueing. *Visual Cognition*, *13*, 29–50.

Helmholtz, H. von. (1866). *Treatise on physiological optics* (J.P.C. Southall, Ed.; Vols. 2 and 3). Rochester, NY: Optic Society of America.

James, W. (1983). *The principles of psychology*. Cambridge, MA: Harvard University Press. (Original work published 1890)

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America*, *49*, 467–477.

Ling, S., & Carrasco, M. (2006). Sustained and transient covert attention enhance the signal via different contrast response functions. *Vision Research*, *46*, 1210–1220.

Ling, S., & Carrasco, M. (2007). Transient covert attention does alter appearance: A reply to Schneider (2006). *Perception & Psychophysics*, *69*, 1051–1058.

Liu, T., Fuller, S., & Carrasco, M. (2006). Attention alters the appearance of motion coherence. *Psychonomic Bulletin & Review*, *13*, 1091–1096.

Liu, T., Pestilli, F., & Carrasco, M. (2005). Transient attention enhances perceptual performance and fMRI response in human visual cortex. *Neuron*, *45*, 469–477.

Loftus, G.R., & Masson, M.E.J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, *1*, 476–490.

Lu, Z.L., & Dosher, B.A. (2000). Spatial attention: Different mechanisms for central and peripheral temporal precues? *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 1534–1548.

Mante, V., Frazor, R.A., Bonin, V., Geisler, W.S., & Carandini, M. (2005). Independence of luminance and contrast in natural scenes and in the early visual system. *Nature Neuroscience*, *8*, 1690–1697.

Martinez-Trujillo, J., & Treue, S. (2002). Attentional modulation strength in cortical area MT depends on stimulus contrast. *Neuron*, *35*, 365–370.

Montagna, B., & Carrasco, M. (2006). Transient covert attention and the perceived rate of flicker. *Journal of Vision*, *6*(9), Article 8. Available from http://www.journalofvision.org/6/9/8/

Muller, H.J., & Rabbitt, P.M. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315–330.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631–1647.

Prinzmetal, W., Long, V., & Leonhardt, J. (2008). Involuntary attention and brightness contrast. *Perception & Psychophysics*, *70*, 1139–1150.

Prinzmetal, W., Nwachuku, I., Bodanski, L., Blumenfeld, L., & Shimizu, N. (1997). The phenomenology of attention: 2. Brightness and contrast. *Consciousness and Cognition*, *6*, 372–412.

Reynolds, J.H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Review of Neuroscience*, *27*, 611–647.

Reynolds, J.H., Pasternak, T., & Desimone, R. (2000). Attention increases sensitivity of V4 neurons. *Neuron*, *26*, 703–714.

Schneider, K.A. (2006). Does attention alter appearance? *Perception & Psychophysics*, *68*, 800–814.

Thomas, J.P., & Gille, J. (1979). Bandwidths of orientation channels in human vision. *Journal of the Optical Society of America*, *69*, 652–660.

Treue, S. (2004). Perceptual enhancement of contrast by attention. *Trends in Cognitive Sciences*, *8*, 435–437.

Tsal, Y., Shalev, L., Zakay, D., & Lubow, R.E. (1994). Attention reduces perceived brightness contrast. *Quarterly Journal of Experimental Psychology A*, *47*, 865–893.

Tse, P.U. (2005). Voluntary attention modulates the brightness of overlapping transparent surfaces. *Vision Research*, *45*, 1095–1098.

Turatto, M., Vescovi, M., & Valsecchi, M. (2007). Attention makes moving objects be perceived to move faster. *Vision Research*, *47*, 166–178.

Wichmann, F.A., & Hill, N.J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics*, *63*, 1293–1313.

Yeshurun, Y., Montagna, B., & Carrasco, M. (2008). On the flexibility of sustained attention and its effects on a texture segmentation task. *Vision Research*, *48*, 80–95.

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