Attention biases decisions but does not alter appearance

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Attention biases decisions but does not alter appearance

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Recently, M. Carrasco, S. Ling, and S. Read (2004) reported that transient visual attentional cues could increase the perceived contrast of Gabor grating targets. We replicated their study using their exact stimuli and procedures. While we were able to reproduce their results, we discovered that the reported attentional effects vanished when we changed the type of decision that subjects performed from a comparative judgment ("which target has higher contrast?") to an equality judgment ("are the two targets equal in contrast?") that is resistant to bias. To ensure that the difference between the judgments was not due to a difference in attentional strategies, we also performed a control experiment in which subjects were instructed on a trial-by-trial basis which judgment to perform only after the stimuli had disappeared. In this experiment, the magnitude of attentional effect for the comparative judgment was diminished but still significant and the equality judgment still measured no effect. We conclude that the reported effects of attention upon appearance can be entirely explained by decision bias, and that attention does not alter appearance.

Keywords: attention, spatial vision, appearance, contrast perception

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Introduction

Directing one's attention to a visual stimulus is well known to enhance the processing of the stimulus: decreasing the response time, improving detection, and increasing the accuracy of identification. However, whether attention actually alters the subjective appearance of the stimulus in addition to facilitating its perceptual processing has been a subject of scientific curiosity and dispute for over one hundred years (for a review, see Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). Most psychologists in the late 19th and early 20th century thought that attention intensified sensations, and William James suggested that this attentional intensification might be nullified by a compensatory mechanism to preserve the veridical appearance of stimuli (James, 1890).

More recently, electrophysiological recordings in extrastriate cortex have shown that attention increases neural firing rates similarly to increases in stimulus contrast (Martínez-Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000), leading some to speculate that attention operates by actually increasing stimulus contrast, which without compensation should manifest in a subjective change in appearance. However, in a previous psychophysical study, attention had been found to reduce response variability but not alter the subjective contrast appearance (Prinzmetal et al., 1997). Nevertheless, when a new psychophysical study reported that attention could increase perceived contrast (Carrasco, Ling, & Read, 2004), it was hailed as the missing link between the neural theories of attention and phenomenology (Luck, 2004; Treue, 2004). In the study, subjects were briefly presented with two peripheral Gabor targets of varying contrasts, one of which could be preceded in its spatial vicinity by a transient cue stimulus. The task of the subjects was to identify which of the two targets had the higher contrast and to judge the orientation of that target. The utility of the extra orientation task is unclear, as is discussed in the next section below. The results indicated that the subjects judged the cued target to have significantly higher contrast than the contrast at which it was actually presented, as inferred by perceptual comparisons to the uncued targets.

In a previous study, we used different stimuli, solid disks rather than Gabors, and were unable to measure any effects of attention upon apparent contrast for targets above the detection threshold (Schneider, 2006). To maximize the location uncertainty and therefore the information content of the cue, the targets were presented at random locations within an annulus rather than at two

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fixed locations. The study was designed to measure sensory interactions between the cues themselves and the targets, and we did find cue effects on the perceived contrast of targets with contrasts near or below the detection threshold. However, these effects were additive over the contrast range rather than multiplicative as would be expected by a contrast gain model of attention, and the cue effects also depended upon the contrast polarity of the cue. Therefore, we concluded that the observed effects of the cues on perceived contrast were likely due to sensory interactions between the cues and targets rather than effects of attention. Ling and Carrasco (2007) found no effects of cue polarity with their suprathreshold Garbor stimuli, and thus it is unlikely their previous results (Carrasco et al., 2004) were due to sensory interactions. However, the lack of any effect of the attentional cues for suprathreshold targets in Schneider (2006) presents a challenge to the findings of Carrasco et al. (2004). Ling and Carrasco suggested that perhaps the ring-shaped cues used in Schneider may have invoked meta-contrast masking that exactly canceled the attentional effects. While such a precise cancellation seems unlikely, we nevertheless decided to try to replicate Carrasco et al. using target and cue stimuli with identical spatiotemporal properties and a range of superthreshold target contrasts including those used in their study.

Locus of the cue effect

The difficulty in designing and interpreting a behavioral experiment intended to measure the effect of attention on appearance is that the cue used to orient attention may have multiple effects along the stimulus-response pathway, as shown in Figure 1.

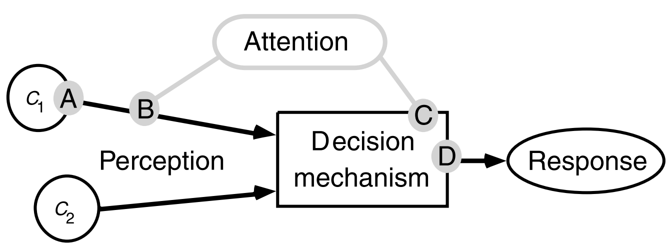

Figure 1. Locus of the cue effect. A pre-cue in the vicinity of a stimulus c_1 can affect the judgment of its contrast relative to another stimulus c_2 at multiple points along the stimulus-response pathway. (A) The cue stimulus could have a low-level sensory interaction with the stimulus. (B) The cue could orient attention towards c_1, perhaps boosting its apparent contrast in the process. (C) Attention could also affect the decision mechanism, prioritizing c_1 and causing subjects to tend to more frequently report it as having higher contrast than c_2 even if the two stimuli were perceptually identical. (D) The presence of a cue differentiates c_1 from c_2 and could also cause a response bias, independent of attention.

Depending on its exact spatial and temporal proximity to a target stimulus, the cue stimulus could interact with the target stimulus at a sensory low-level site, through brightness induction or some other mechanism that could affect the registration of the stimuli even at the retinal level. For example, in a previous study, we found an additive effect of the cue that depended on its contrast polarity, such that a dark cue reduced the apparent contrast of perithreshold disc targets and a light cue enhanced it (Schneider, 2006). Cues can orient attention to a target, which, in addition to potentially altering the appearance of a stimulus, could initiate a variety of other mechanisms that might prioritize the cued target in a behavioral choice task. Attentional selection shortens reaction time (Posner, 1980), improves discriminability (Lee, Itti, Koch, & Braun, 1999), reduces variance (Prinzmetal et al., 1997), lowers detection thresholds (Lu & Dosher, 1998), and generally increases the salience of a target. In addition, transient cues cause conspicuous phenomena, such as motion induction (Jancke, Chavane, Naaman, & Grinvald, 2004) and changes in temporal order (Schneider & Bavelier, 2003), whose spatiotemporal criteria resemble those required for attention. In addition to the various effects of a cue on a target, even the mere presence of a cue associated with one target and not the other could prioritize that target and cause a simple response bias favoring it.

Carrasco et al. (2004) performed three control experiments to try to rule out biases as explanations for their results. By using a post-cue in one experiment and by demonstrating that their appearance effect depended on the cue lead time in another, they showed that their results were likely caused by an effect of the cue and not merely its presence. They also tried to address possible biases in the decision mechanism in another control experiment in which subjects were required to choose which target had the lower instead of higher contrast. This procedure can reveal biases (Frey, 1990), and in their case it changed the slopes of the psychometric functions and reduced but did not eliminate the cuing effect. This manipulation is not necessarily effective in eliminating biases, however, given the possibility that subjects could continue to preferentially associate the cued target with higher contrast and simply invert their responses. Although the control experiments performed in Carrasco et al. (2004) narrowed the possible sources of bias, they did not eliminate the possibility that the cue, through any of many possible mechanisms, could simply increase the salience of the cued target and thereby prioritize it for selection. Increasing the contrast of a stimulus also increases its salience, but salience and contrast are not identical properties. For example, a Gabor pattern with a unique orientation among a uniform field will be highly salient compared to its neighbors with subjectively equal contrasts.

The dual task used in Carrasco et al. (2004) may serve to exacerbate the potential bias problem. In their study, subjects were required to judge the orientation of the target deemed to have the higher contrast. The subjects therefore had to perform two separate discrimination tasks on the briefly presented targets. First they had to determine which of the two targets had the higher contrast, and then they had to determine the orientation of this target. Since the subjects had two judgments to complete without the luxury of prolonged period for information accrual or decision, it would be advantageous for them to make a quick determination of the relative contrasts of the two targets in order to move on to the secondary orientation discrimination. Especially when the subjects were completely uncertain as to which target had the higher contrast, they might tend choose to judge the orientation of the cued target because their attention was already drawn there, and they would not have to disengage their attention towards the other target in order to make the orientation discrimination; also since attention increases salience and accuracy, the subjects would be more confident in their responses if they chose the cued target.

The focus of the present study then is to determine whether attentional biasing of the decision process—an attention-induced assignment of higher priority to the cued target than the uncued target—can explain the results of Carrasco et al. (2004). To do so, we designed a task with a different decision process than the comparative judgment used in Carrasco et al. (2004). We had subjects perform two types of perceptual judgments in separate sessions. In one session, subjects judged whether the two targets had the same or different contrast ("equality judgment"). In another session, subjects judged which target had the higher contrast ("comparative judgment"). In a third session, replicating the task in Carrasco et al. (2004), subjects performed the comparative judgment and additionally determined the orientation of the target deemed to have the higher contrast ("comparative judgment plus orientation"). In a control experiment, to ensure that the results could not be explained by a difference in attentional strategies between the judgments, subjects were shown an identical set of stimuli but were only informed which judgment to perform on each trial after the target stimuli had disappeared.

Signal theory

Comparative judgment

In the comparative judgment used in Carrasco et al. (2004), the subjects must identify which of two targets has the higher contrast. The point of subjective equality (PSE), at which the slope of the psychometric function is steepest, is located at the point of maximum uncertainty, where subjects are most susceptible to influence from even the smallest bit of information that might tip the balance in favor of one of the two targets. Given the control experiments in Carrasco et al. (2004), we can be confident that their reported effects of the transient cues on the subjects' responses are due to attention or some process with similar temporal dynamics. However, as noted above, the cues bear a number of consequences that could prioritize one target over the other and therefore bias the decision mechanism yet leave the veridical appearance of the targets intact. During a comparative judgment, this prioritization could have the same effect on subjects' responses as would instructing them, for example, to always choose the cued target unless they were extremely certain that the uncued target was higher in contrast.

To model the comparative judgment, we assume that the input to the decision mechanism is the difference in perceived contrast between the cued (c_1) and uncued (c_2) target stimuli. As depicted in Figure 2, this difference can be parameterized as a normal distribution $N(\Delta c + \alpha, \sigma)$ with mean $\Delta c + \alpha$ (where Δc is the actual difference in contrast, and α is the hypothesized attentional boost in the perceived contrast of the cued target) and variance σ^2. A subject has a choice of criterion τ, which, as shown in Figure 2A, is the difference in contrast above which the subject will report that the cued stimulus has the higher contrast. If $\tau = 0$, then the judgment is unbiased, while if

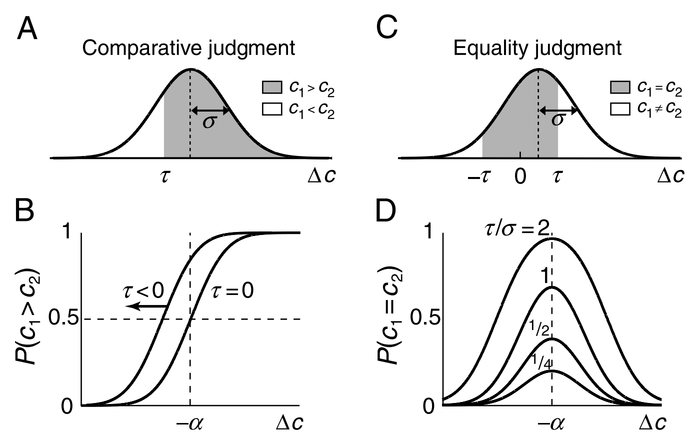

Figure 2. Model of the decision mechanism. (A) The difference in contrast Δc between two stimuli with contrasts c_1 and c_2 is modeled as a normal distribution with variance σ^2. In a comparative judgment, if c_1 is greater than c_2 by at least a criterion quantity τ, then a subject will report "$c_1 > c_2$" with a probability determined by the area of the shaded region. (B) If attention boosts the contrast of c_1 by a factor α, then c_1 and c_2 appear to be equal in contrast when $\Delta c = -\alpha$; here, if $\tau = 0$, the judgment is unbiased, and the subject is equally likely to report either stimulus as having a higher contrast. However, if $\tau \neq 0$, then the subject is biased to report one of the stimuli, which will shift the psychometric curve and confound the measurement of α. In fact, α and τ have identical effects and are experimentally indistinguishable. (C) In the equality judgment, subjects will report "$c_1 = c_2$" when $|\Delta c| < \tau$, with a probability depending on the area of the shaded region. (D) The choice of criterion τ affects the response probability but does not interact with the central tendency and hence the measurement of α.

$\tau < 0$, then the subject is biased to report that the cued target has the higher contrast, and if $\tau > 0$, biased to report the uncued target.

Given a particular set of stimuli, the probability that a subject will report the cued target having higher contrast is equal to the fraction of the area of the perceived contrast difference distribution that is greater than τ. That is, $P(\text{“}c_1 > c_2\text{”}) = \int_\tau^\infty \varphi\left(\frac{u-\Delta c-\alpha}{\sigma}\right)du = 1-\Phi\left(\frac{\tau-\Delta c-\alpha}{\sigma}\right)$, where $\varphi(x) \equiv \frac{1}{\sqrt{2\pi}}e^{-x^2/2}$ is the probability density function of the normal distribution and $\Phi(x) \equiv \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-u^2/2}du$ is the cumulative distribution function. As shown in Figure 2B, the comparative judgment forms a psychometric function over the range of contrast differences. The PSE occurs at the point of maximum uncertainty, when $P(\text{“}c_1 > c_2\text{”}) = 1/2$, which implies that $\Delta c + \alpha = \tau$. A subject's criterion, τ, and the hypothesized attentional boost in perceived contrast of the cued target, α, are degenerate and thus experimentally indistinguishable.

Equality judgment

To distinguish between the possibilities that attention alters appearance or merely biases the decision mechanism, we employed an equality judgment in addition to the comparative judgment. An equality judgment involves a different decision mechanism but operates on the same perceptual input. If attention actually changes the appearance and increases the perceived contrast of the cued target ($\alpha > 0$), then this should cause subjects to be more likely to respond that the cued target had an unequal contrast to an identical uncued target. Likewise, a subject ought to be more likely to respond that a lower-contrast cued target had equal contrast to a higher-contrast uncued target. If on the other hand attention does not actually alter appearance ($\alpha = 0$) but only serves to prioritize the cued target and thereby influence the decision process in the comparative judgment, then we would expect that attention would not have the identical effect on the measured PSE as determined by the equality judgment that uses a different decision process.

The equality judgment, shown in Figure 2C, is a decision mechanism that operates on the same difference in perceived contrast distribution as does the comparative judgment. Subjects choose a criterion τ and report the two stimuli as being equal in contrast if the absolute difference in their perceived contrast is less than τ, i.e., $|\Delta c + \alpha| < \tau$. Therefore, the probability that a subject will report the two stimuli having equal contrast is equal to the fraction of the area of the perceived contrast distribution between $-\tau$ and $+\tau$[1]. That is, $P(\text{“}c_1 = c_2\text{”}) = \int_{-\tau}^{\tau} \varphi\left(\frac{u-\Delta c-\alpha}{\sigma}\right)du = \Phi\left(\frac{\tau-\Delta c-\alpha}{\sigma}\right) - \Phi\left(\frac{-\tau-\Delta c-\alpha}{\sigma}\right)$. The PSE occurs at the maximum of this bell-shaped function, when $\Delta c + \alpha = 0$, which is independent of the subject's choice of τ. As shown in Figure 2D, the magnitude of the equality judgment scales with τ, but the central tendency is unperturbed. Therefore, the PSE as determined by the equality judgment depends only on the relative perceived contrasts of the two stimuli and is not affected by any biases that may be present in the decision process.

Methods

Subjects

Eighteen subjects (10 male), mean age 22 years (range 19–33), were paid to participate in the study. Fourteen participated in three separate sessions in the main experiment. Eight of these and an additional four subjects participated in the control experiment. All subjects had normal or corrected-to-normal visual acuity and gave their written, informed consent under the guidelines of the Research Subjects Review Board at the University of Rochester.

Apparatus

The stimuli were generated on a Macintosh G5 computer (Apple, Inc., Cupertino, CA) using the Matlab (The Math Works, Inc., Natick, MA) programming language and displayed using Psychophysics Toolbox 3 functions (Brainard, 1997; Pelli, 1997) on a ViewSonic P220 monitor (ViewSonic Corp., Walnut, CA) with a refresh rate of 85 Hz and driven by a GeForce FX 5200 video card (NVIDIA Corp., Santa Clara, CA). The stimulus timing reported below was constrained by the refresh rate and was rounded up to an integral multiple of the 11.76-ms frame rate. The output channels of the video card were combined with a video attenuator device (Video Switcher, Xiangrui Li, Los Angeles, CA) to enable 12-bit precision in the gray-scale luminance values (Li, Lu, Xu, Jin, & Zhou, 2003). The gamma function and luminance of the monitor were measured using an LS-100 photometer (Konica Minolta Photo Imaging USA, Mahwah, NJ).

Visual stimuli

A diagram of the stimulus sequence is shown in Figure 3. Two Gabor stimuli targets, sine gratings with spatial frequencies of 2 or 4 cpd, zero phase and Gaussian envelopes with a standard deviation of 1°, were simultaneously presented for 40 ms on a uniform gray field. The centers of the targets were located 4° eccentricity to the right or left of the fixation point. For the equality and comparative judgments, the Gabors were oriented vertically. For the comparative judgment plus orientation, the Gabors were independently and randomly rotated 45° clockwise or counterclockwise. One hundred twenty

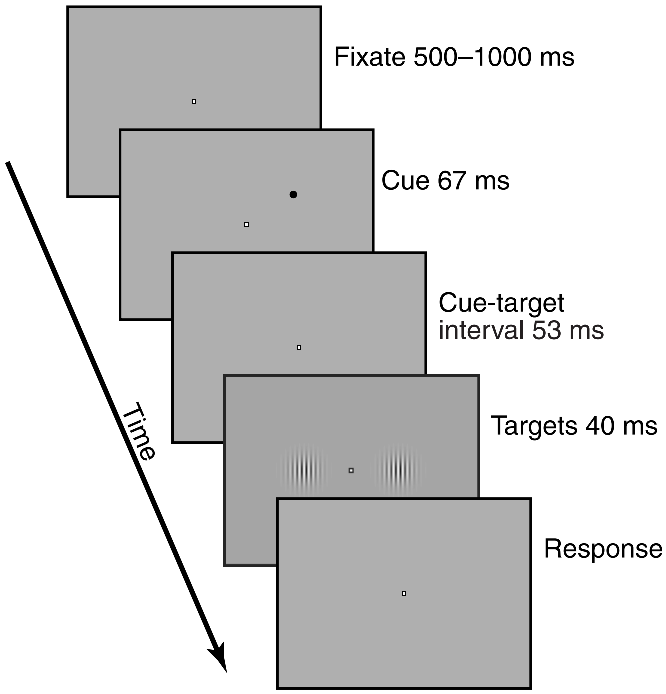

Figure 3. Stimulus sequence. Subjects fixated for 500–1000 ms, after which a cue appeared at 4° eccentricity on the left or right. The cue disappeared after 67 ms, and 120 ms after the cue onset, two Gabor grating stimuli appeared centered at the same eccentricity, one of which was slightly below the location at which the cue had appeared. After 40 ms, the stimuli disappeared and subjects reported their relative contrasts.

milliseconds before the onset of the targets, a 0.3° diameter black dot was presented for 67 ms at the location 1.5° directly above the center of one of the two targets. The luminance contrasts of the two targets were distinct and were defined as $\frac{L_1-L_2}{L_1+L_2}$, where L_1 is the maximum luminance of the sine wave component of the Gabor and L_2 is the minimum. The mean luminance of the sine wave components equaled the background luminance, 85 cd/m^2. The contrast of the cued target was 15%, 20%, 25%, 30%, or 35%, and the contrast of the uncued target was chosen from an evenly distributed logarithmic range of contrasts spanning ±1 natural log units relative to the cued target contrast, i.e., multiples of 0.36, 0.47, 0.61, 0.77, 1.0, 1.3, 1.6, 2.1, and 2.7. The overall range of contrasts used in this study was 5.5–95%.

Procedure

Subjects were seated in a dark room and viewed the display from a distance of 50 cm. The cue stimulus would appear randomly on the left or right for each trial. Each of the 45 combinations of 5 contrast levels of the cued target and 9 relative contrast levels of the uncued target was repeated 20 times, for a total of 900 trials. The pairs of target contrasts were randomly interleaved throughout the experimental session. The spatial frequencies of the two targets were equal but were randomly chosen from the two possibilities for each trial.

Subjects performed one of three types of judgments in separate experimental sessions on separate days. In one session, subjects judged whether the contrasts of the two targets were equal or not (equality judgment). In another session, subjects judged which of the two targets had the higher contrast (comparative judgment). In a third session, subjects reported the orientation (tilted left or right) of the target that had the higher contrast (comparative judgment plus orientation). Subjects indicated their responses by pressing a key on the keyboard. For the equality judgment, subjects pressed the *s* or *d* keys to indicate whether the targets were the same or different. For the comparative judgment, the subjects pressed the left or right arrow keys to indicate whether the target with the higher contrast was located to the left or right of fixation. For the comparative judgment plus orientation, the subjects pressed the *s, d, k,* and *l* keys to indicate that the target on the left had higher contrast and was tilted to the left (*s*) or right (*d*) or that the target on the right had higher contrast and was tilted to the left (*k*) or right (*l*). Reaction time was recorded but there was no time limit for the responses. The cue stimulus for the next trial would appear 0.5–1 s after the response was made. The experimental sessions lasted approximately 1 hour, during which the observers were automatically allowed to rest and break fixation after every fifty stimuli presentations, resuming the experiment when ready.

In the control experiment, the stimuli and procedures were identical with the following exceptions. The fixation point consisted of the superimposed characters = and +. When the target stimuli disappeared, one of the two characters at the fixation point also disappeared, and the other character remained until a response was made and indicated to the subject which of the two judgments to perform: = for the equality judgment and + for the comparative judgment. If the equality judgment was instructed, the *s* and *d* keys were pressed to indicate whether the targets were the same or different contrast, respectively. If the comparative judgment was instructed, the left and right arrow keys were pressed to indicate whether the left or right target had the higher contrast. Only key presses from the appropriate judgment were accepted; extraneous keys were ignored. The subjects participated in two separate sessions on different days. In each session, ten repetitions were performed for each of the cue and target contrast combinations and each judgment type. Data from the two sessions were combined.

Data analysis

Data from the two different target spatial frequencies were combined and not analyzed separately. The equivalent contrasts of the cued targets were determined by fitting the subjects' responses to models (Schneider &

Bavelier, 2003) through a global maximum likelihood optimization procedure. The comparative judgment data were fit to a cumulative normal distribution, $1 - \Phi(\frac{\Delta c + \alpha}{\sigma})$, and the equality judgment data to a difference of cumulative normal distributions, $\Phi\left(\frac{\tau - \Delta c - \alpha}{\sigma}\right) - \Phi\left(\frac{-\tau - \Delta c - \alpha}{\sigma}\right)$, where τ is the contrast difference criterion, Δc is the actual difference in contrast between the cued target to the uncued target, σ^2 is the variance of the contrast difference, and α is the potential boost in perceived contrast of the cued target relative to the uncued target. α was determined as the difference in contrast where the PSE occurs: the point at which the psychometric function for the comparative judgment crosses 50% or the maximal point of the equality judgment function. Each parameter has units of logarithmic contrast. The perceived contrast at the PSE was calculated as $c' = ce^{\alpha}$ for each actual contrast level c of the cued target. The variances of the estimates of the model parameters were derived for each subject by assuming that the likelihood function is distributed in parameter space approximately normal near the optimal parameters (MacKay, 1992), and these variances were used to compute the weighted mean of each model parameter across subjects (Schneider, 2006).

Results

Equivalent contrast

Typical responses for the comparative and equality judgments are shown in Figure 4 for a single subject a single contrast level of the cued target.

For each contrast level of the cued target, the subjects made comparisons to uncued targets presented from one of nine different contrasts. These data formed distributions that we, for each judgment type and contrast level of the cued target, fit to a psychometric function derived from the response model. We inferred the PSEs from the fit parameters for each subject and used them to calculate the equivalent apparent contrasts for each actual contrast level of the cued target. During the fitting procedure, we obtained an estimate of the variance of each fit parameter and used this to calculate a weighted mean across subjects. These weighted means of the reported apparent contrast of the cued target are plotted against the actual contrasts for each judgment type in Figure 5.

For the equality judgment, the cue had no significant effect (two-tailed t-test of the weighted mean, $t_{13} < 0.9$, $p \geq .4$, error bars indicate the 95% confidence intervals) on the perceived contrast of the targets at any of the contrast levels of the cued target—the contrast judgments were veridical across the range of contrasts tested. However, for the two comparative judgments, the contrasts of the cued targets were judged to be highly significantly ($t_{13} > 3.2$, $p < .01$) greater than their actual contrasts for each of the contrast levels tested. There was no significant difference between the apparent contrasts as measured by the two different comparative judgments, at any of the individual contrast levels ($t_{13} < 0.9$, $p > .4$) or between the weighted means across all contrast levels ($t_4 = 1.17$, $p = .31$), although the results of each comparative judgment were significantly different than those measured with the equality judgment at nearly every contrast level ($t_{13} > 2.1$, $p < .05$, except the 25% contrast comparison for the comparative judgment, where $t_{13} = 1.67$, $p = .12$). Whether the subjects additionally determined the orientation of the higher contrast target had little effect.

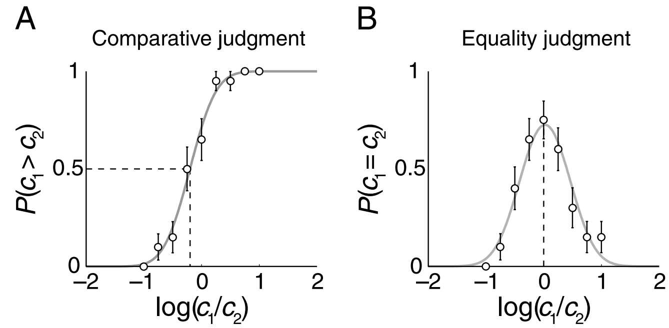

Figure 4. Typical responses from one subject for one contrast level of the cued target. For each contrast level of the cued target (c_1, 15–35%), the uncued target was presented at a range of surrounding contrasts (c_2). The abscissa represents the natural logarithm of the ratio of the cued target contrast to the uncued target contrast. The subjects performed two different types of judgments on a set of identical stimuli in separate sessions. (A) In the comparative judgment, the subjects reported which of the two targets appeared to have the higher contrast, and the ordinate represents the fraction of responses in which a subject indicated the cued target had higher contrast. The circular markers indicate the mean response for 20 repetitions, and the error bars depict the standard error of the mean. From the model fit to the distribution of responses, indicated by the solid gray line, the point of subjective equality (PSE) was determined as the point at which the subject was equally likely to report either target as having the higher contrast (P = 1/2). (B) In the equality judgment, the subjects reported whether or not the two stimuli were equal in contrast; the ordinate represents the fraction of affirmative responses. The PSE was determined from the model fit as the point of maximal equality.

Response time

The mean across subjects of each subject's median response time, as measured from the onset of the targets and pooled across contrast levels, was 790 ± 76 ms for the equality judgment, 531 ± 47 ms for the comparative judgment, and 728 ± 86 ms for the comparative judgment plus orientation. Response times for the equality judgment and comparative judgment plus orientation were both

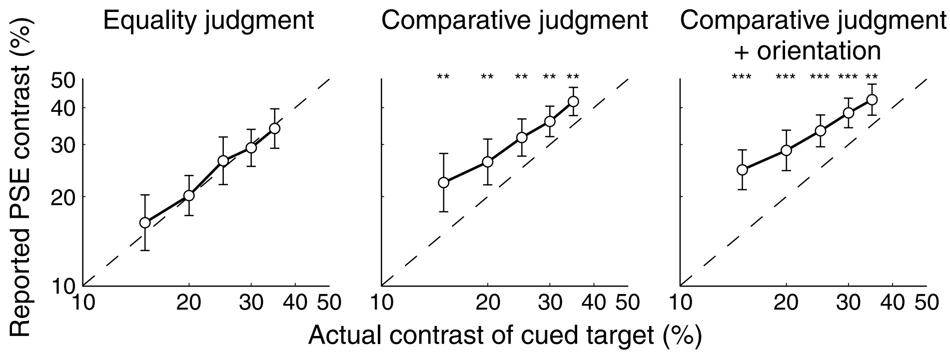

Figure 5. Results of main experiment. Subjects performed three different judgments in three separate experimental sessions. In one session the subjects judged whether the two targets were equal in contrast or not ("equality judgment"). In another session, the subjects judged which of the two targets was higher in contrast ("comparative judgment"). In the third session, a replication of the task used in Carrasco et al. (2004), subjects judged the orientation of the target judged to have the higher contrast ("comparative judgment + orientation"). The actual contrast of the cued target is plotted against the point of subjective equality (PSE) determined from the distribution of subjects' comparisons to uncued targets with neighboring contrasts. The data points are the weighted average from 14 subjects, and the error bars indicate the 95% confidence intervals of the weighted mean. The dashed lines demark the location of veridical judgments, where the actual and reported contrasts are equal. Asterisks indicate the level of significance in the difference between the reported and actual contrasts: *$p < .05$, **$p < .01$, ***$p < .001$.

significantly slower than those for the comparative judgment (t_{13} = 7.76, p = .0000031 and t_{13} = 2.72, p = .017, respectively) but did not significantly differ from each other (t_{13} = 0.71, p = .49).

Criterion and variance parameters

The weighted mean values of the σ parameter across subjects and contrast levels were 0.410 ± 0.021, 0.450 ± 0.035, and 0.382 ± 0.023, respectively, for the equality, comparative, and comparative plus orientation judgments. There was a trend for σ to be somewhat larger for the lower contrast levels. This parameter did not significantly differ among the judgments at any individual contrast level ($t_{13} < 1$, $p > .3$ for the equality judgment compared to the two comparative judgments; 7.76, $t_{13} < 1.2$, $p > .2$ for the two comparative judgments, except at the 25% contrast level, where t_{13} = 1.80, p = .10) or averaged across contrast levels ($t_4 < 1.7$, $p > .18$). This suggests that each decision mechanism operated upon similar underlying distribution of the difference in contrast between the targets. For the equality judgment, the weighted mean of the criterion τ across subjects and contrast levels was 0.421 ± 0.020. For comparison with the equality judgment functions in Figure 2D, note that $\tau/\sigma \approx 1$.

Accuracy on the orientation task

The subjects were generally at ceiling at judging the correct orientation of their selected targets in the comparative judgment plus orientation task. When the subjects chose a cued target, they correctly identified its orientation 94.17 ± 1.8% of the time compared to 94.17 ± 1.9% when they chose an uncued target. However, the set of uncued targets contained a larger range of contrasts. Restricting the analysis to only those uncued targets belonging to the set of possible cued target contrasts, the subjects correctly identified 93.30 ± 2.9% of the target orientations. The accuracy of identification for cued and uncued targets was not significantly different (t_{13} = 0.47, p = .65).

Control experiment

In the control experiment, on each trial the subjects did not know whether they would perform the comparative or equality judgment until after the stimuli had disappeared. Subjects remarked that this experiment was more difficult than the main experiment, and several reported the strategy of mainly preparing for the comparative judgment and switching to the equality judgment when necessary. The data were analyzed as in the main experiment. The equivalent contrasts are plotted for each judgment in Figure 6.

For the equality judgment, the reported apparent contrast was not significantly different from the actual contrast at any of the contrast levels. However, at the 20% contrast level, the difference was marginally significant (t_{11} = 1.92, p = .081). For the comparative judgment, the reported apparent contrast was significantly greater than the actual contrast for the 15 and 20% contrast levels of the cued target (t_{11} = 3.26, p = .0075 and t_{11} = 2.51, p = .029, respectively), but not for the higher contrasts, although they trended in the same direction. The mean response times for the equality and comparative judgments in this experiment were 1263 ± 76 ms and 928 ± 66 ms, respectively, which differed significantly from each other (t_{11} = 6.21, p = .000066) and were significantly slower

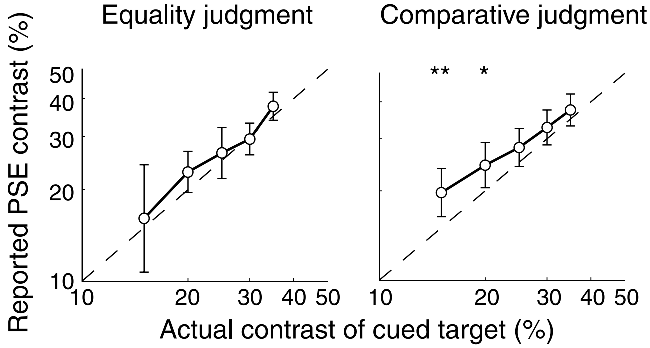

Figure 6. Results of control experiment. In this experiment, the two judgment tasks were mixed throughout the session, and subjects were instructed which judgment to perform on each trial only after the stimuli disappeared. Conventions as in Figure 5.

than their counterparts in the main experiment (t_{24} = 4.37, p = .00021 and t_{24} = 4.98, p = .000043, respectively). The weighted mean of the σ parameter across subjects and contrast level was 0.376 ± 0.040 and 0.411 ± 0.024 for the equality and comparative judgments, respectively, which did not significantly differ from each other (t_4 = 0.74, p = .50) or their counterparts in the main experiment (t_4 = 0.74, p = .50 and t_4 = 0.92, p = .41, respectively). The weighted mean across subjects and contrast levels for the criterion τ in the equality judgment was 0.354 ± 0.030, which did not significantly differ from that in the main experiment (t_4 = 1.85, p = .14). As in the main experiment, $\tau/\sigma \approx 1$.

Discussion

The only experimental variable that differed between the equality judgment experiment and the comparative judgment experiments was the type of judgment performed by the subjects. The stimuli and attentional conditions were the same, and thus the subjects' perceptions should be the same. If the attentional cues actually changed the appearance of their targets, then the type of judgment performed by the subjects should be inconsequential. Since the cues had no effect in the equality judgment experiment, we can eliminate the hypothesis that attention altered the contrast appearance of the stimuli.

The control experiment makes it even more clear that attention is affecting the decision process and not perception. Since the stimuli disappeared before the subjects were instructed which judgment to make, we could rule out the possibility that predisposition to one judgment or the other could have invoked different perceptual mechanisms. Although the subjects found this experiment more difficult and the effects were weaker, the cues did have significant effect at the lowest two contrast levels for the comparative judgment but no effect for the equality judgment. Since the perception and appearance of the stimuli was identical between the two types of judgments, the effect of the cues must have been added in the decision process during the comparative but not equality judgment. This eliminates the possibility that the lack of an effect of attention upon apparent contrast as measured in the equality judgment could be explained by a different attentional state or strategy employed by the subjects.

What then is the explanation for the significant effects in the comparative judgment experiments, and indeed, the results of Carrasco et al. (2004)? Comparative judgments are extremely susceptible to biases because the PSE is located at the point of maximum uncertainty. When forced to choose which target has the higher contrast when in fact the targets are equal or nearly equal in contrast, subjects might have a tendency to respond that a cued target has the higher contrast. Other studies have also attributed the reported effects to biases (Prinzmetal, Long, & Leonhardt, 2008). Unlike the comparative judgment, however, the equality judgment is immune to such biases—the response options in the equality judgment are not bound to individual targets, and general preferences for one of the responses do not affect its measurement of the PSE (see Methods; Schneider & Bavelier, 2003). Simple response biases, however, cannot entirely explain the results. Carrasco et al. (2004) performed a control experiment wherein subjects judged which target had the lower instead of higher contrast. If subjects had preferentially chosen the cued targets irrespective of the task requirements for some reason, for example, because their attention had already been engaged and a switching cost would be incurred by scrutinizing the uncued targets, then this control experiment would have shown that the cued targets were perceived as having lower contrast; this was not the case. The bias to associate the cued target with higher contrast must occur during the decision process rather than during the response, which could simply be inverted in the "lower" task.

This decision bias seems to be caused by attention because its magnitude is dynamic and depends on the cue lead time similarly to other attentional effects (Carrasco et al., 2004; Schneider & Bavelier, 2003). Attention must operate on the targets through a mechanism that influences the decision process but leaves their appearance intact, for example by increasing their salience or the quality or quantity of information about them (Prinzmetal et al., 1997), or perhaps simply flagging them as important. Although the effects of attention are not generally interpreted as changes in decision criteria, there are some proponents of the idea (Gorea & Sagi, 2005).

In addition to the Carrasco et al. (2004) study on apparent contrast, a series of subsequent studies have reported that attention alters appearance, including apparent spatial frequency and gap size (Gobell & Carrasco, 2005), motion coherence (Liu, Fuller, & Carrasco, 2006), color saturation (Fuller & Carrasco, 2006), flicker rate (Montagna & Carrasco, 2006), and the speed (Turatto, Vescovi, & Valsecchi, 2007) and size (Anton-Erxleben, Henrich, & Treue, 2007) of moving patterns. While the present results cannot be extrapolated beyond contrast perception, all of these studies used comparative judgments and are therefore subject to the same confound between the potentially biased choice of criterion and the measured PSE. It is interesting to note that in each of these studies, attention is reported to modify the appearance of stimuli to increase their salience. An important point to be drawn from the results of the present study, as was demonstrated previously (Schneider & Bavelier, 2003), is that any study whose results reply upon a comparative perceptual judgment between two stimuli that differ by more than a single dimension, e.g., the presence of a cue in addition to a difference in contrast, should be viewed with extreme skepticism, because the additional differences may have unintended influences.

Conclusion

Attentional cues may increase the salience and priority of stimuli and thereby, depending on the task demands, incite post-perceptual decision biases. However, these processes do not prohibit the veridical perception of sensory attributes. William James (1890) had it right when he wrote, "The intensification which may be brought about by attention seems never to lead us astray" (p. 426).

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Footnote

[1]In choosing symmetric criteria, we assume the equipotentiality of the contrasts of the two targets. That is, the two targets should appear no more or less equal in contrast depending on whether the cued target is higher or lower in contrast compared to the uncued target. A violation of this assumption would imply that subjects utilized information other than the perceived contrasts of the targets in order to make their decisions, which would support the thesis of this study. Furthermore, asymmetric criteria would result in skewed psychometric functions, which were not generally observed (e.g., Figure 4B).

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