Research Article

Attention Alters the Appearance of Spatial Frequency and Gap Size

Joetta Gobell and Marisa Carrasco

Department of Psychology and Center for Neural Science, New York University

ABSTRACT—***Transient attention is the automatic and short-lasting preferential processing of an area in visual space initiated by sudden stimulation in the same vicinity. Transient attention enhances early visual processing in a variety of dimensions, increasing contrast sensitivity, spatial resolution, and acuity. A recent study established that the increase in contrast sensitivity is accompanied by an increase in apparent contrast. In the present study, we investigated whether the effects of transient attention on spatial resolution and acuity are accompanied by corresponding phenomenological changes in these dimensions. The data indicate that transient attention increases the apparent spatial frequency of Gabor stimuli (Experiment 1) and increases apparent gap size in a Landolt-square acuity task (Experiment 2). Transient attention not only affects basic visual processing—it changes what one experiences.***

Sudden stimulation in the visual field quickly and automatically draws attention to the stimulated location—for example, allowing a driver to notice a movement on the roadside and prepare to react, long before recognizing it as a child's ball rolling into the street. This stimulus-driven, involuntary process is referred to as *transient attention*. It is distinguished from the voluntary deployment of attention (*sustained attention*) not only by its automaticity, but also by its temporal dynamics. Transient attention is deployed quickly and decays soon after, whereas sustained attention is deployed more slowly and can be maintained longer (Jonides, 1981; Nakayama & Mackeben, 1989). Both transient and sustained attention operate covertly, in the absence of eye movements. Here we focus exclusively on transient covert attention, henceforth simply *attention*.

It has been established that attention affects several dimensions of early vision: rate of information accrual (Carrasco, Giordano, & McElree, 2004; Carrasco & McElree, 2001), orientation discrimination and acuity (Baldassi & Burr, 2000; Morgan, Ward, & Castet, 1998), spatial resolution (Balz & Hock, 1997; Tsal & Shalev, 1996; Yeshurun & Carrasco, 1998, 2000), acuity (Carrasco, Williams, & Yeshurun, 2002; Shalev & Tsal, 2002; Yeshurun & Carrasco, 1999), and contrast sensitivity (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Foley & Schwartz, 1998; Lu & Dosher, 1998; Solomon, Lavie, & Morgan, 1997). Although scientists and philosophers like James, Wundt, Fechner, and Helmholtz have debated the critical issue of whether attention alters appearance for more than a century, few studies have investigated this issue directly (Carrasco, Ling, & Read, 2004).

Prior psychophysical and neurophysiological data demonstrating an increase in contrast sensitivity with attention suggest that the brain responds as if the stimulus contrast is increased (e.g., Cameron et al., 2002; Reynolds & Chelazzi, 2004; Reynolds, Chelazzi, & Desimone, 1999). In fact, a recent study showed that a change in apparent contrast accompanies the increase in contrast sensitivity—attending to a stimulus causes it to appear higher in contrast (Carrasco, Ling, & Read, 2004). The innovative paradigm used in that study makes it possible to assess effects of spatial cuing on appearance and can be used to address other questions about phenomenological experience, so that subjective experience can be studied more objectively (Luck, 2004; Treue, 2004).

In the experiments reported here, we used this paradigm to focus on spatial resolution and acuity. Using a texture-segmentation task, Yeshurun and Carrasco (1998, 2000) demonstrated that attention increases spatial resolution, even when this increase is detrimental to performance. Observers detected a target

Address correspondence to Joetta Gobell, New York University, Department of Psychology/CNS, 6 Washington Pl., 8th Floor, New York, NY 10003; e-mail: joetta@cns.nyu.edu.

patch of texture within a background texture of a different orientation. Performance peaked at parafoveal locations and fell with both increasing and decreasing eccentricity. The central performance drop has been explained as a mismatch between filter size and the texture scale (Gurnsey, Pearson, & Day, 1996; von Berg, Ziebell, & Stiehl, 2002). When the target location was cued prior to target onset, the performance peak shifted to even farther eccentricities, and the central performance drop became more pronounced. This indicates that attention improved performance where resolution is low for the texture scale (i.e., peripheral locations) and, crucially, that attention further impaired performance at central locations, where resolution is already too high for the texture scale. This counterintuitive attentional impairment at central locations can be explained only by increased spatial resolution. Yeshurun and Carrasco (2000) hypothesized that attention enhances spatial resolution by increasing sensitivity to high spatial frequencies.

Consistent with this hypothesis, the central performance drop was diminished and the central attentional impairment was eliminated when observers selectively adapted to high spatial frequencies or high frequencies were masked (Ho, Loula, & Carrasco, 2002). In Experiment 1, we investigated whether an attention-driven increase in spatial resolution is accompanied by an increase in apparent spatial frequency. That is, does attending to a stimulus cause it to appear higher in frequency?

Attention also improves performance in an acuity task in which observers are briefly presented with a line or square outline and report the location of a gap in the stimulus (Carrasco et al., 2002; Shalev & Tsal, 2002; Yeshurun & Carrasco, 1999). Given that detecting smaller gaps requires the processing of higher spatial frequencies, this improvement in acuity is consistent with the hypothesis that attention shifts sensitivity to higher frequencies. In Experiment 2, we investigated whether this shift is accompanied by an increase in apparent gap size. That is, does attending to a Landolt square cause its gap to appear larger?

EXPERIMENT 1: SPATIAL FREQUENCY

Method

Participants

Experiment 1 had 24 participants; not all participants were involved in each condition. Thirteen were experienced psychophysical observers; 2 were not naive. All participants had normal or corrected-to-normal vision.

Apparatus

The stimuli for the experiment were generated using Matlab and Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) with an Apple G4 Power Macintosh computer and were displayed on a gamma-corrected Viewsonic P810 21-in. monitor (1600 $\times$ 1200 pixels; 75 Hz). A video attenuator drove only the green gun, to increase the possible set of distinct luminance levels ($\sim$12.6 bits).

Stimuli

The stimulus sequence consisted of a fixation display, a cue display, and a Gabor display. The fixation display contained a black fixation square ($0.1^\circ \times 0.1^\circ$) at the center of a green background (12.2 cd/m^2). The cue display contained the fixation square and a cue—a black circle (0.3° in diameter) appearing either at fixation (neutral cue) or 1.5° above the horizontal meridian, centered at 4° eccentricity to the left or right of fixation (peripheral cue). The peripheral cue was designed to deploy attention to one of two locations, whereas the neutral cue did not. Both cues provided information regarding the temporal onset of the Gabors but were otherwise uninformative. The Gabor display contained the fixation square and two Gabor patches (sine waves in circular Gaussian envelopes). The 50%-contrast Gabors were tilted $\pm 5^\circ$ from vertical, with a space constant of 2°. They were centered at 4° eccentricity to the left and right of fixation, on the horizontal meridian, 1.5° below the peripheral cue. On each trial, one of the Gabors (the standard) had a spatial frequency of either 2.5 or 3.5 cycles/deg, and the other Gabor (the test) had a spatial frequency chosen from 11 values ranging ± 1 cycles/deg around the standard. Additionally, we ran a high-spatial-frequency condition in which the standard frequency was either 5.5 or 7.5 cycles/deg and the test frequency was chosen from 15 values ranging ± 2.25 cycles/deg around the standard.

Observers indicated the orientation (left or right) of the Gabor of higher spatial frequency. The cue location, the Gabor orientations, and the left/right locations of the standard and test Gabors were chosen randomly on each trial. This rendered the cue uninformative, as it indicated neither the orientations of the Gabors nor which Gabor would be of higher spatial frequency.

Procedure

The procedure was adapted from that of Carrasco, Ling, and Read (2004), an investigation that evaluated whether attention alters apparent contrast. Participants completed 50 practice and 1,000 experimental trials. Participants viewed the stimuli binocularly at a distance of 57 cm (114 cm for the high-frequency standard) and were instructed to fixate. A chin rest stabilized the head.

As shown in Figure 1a, a trial consisted of a 300-ms fixation, followed by a neutral or peripheral cue for 67 ms. After a 53-ms interstimulus interval (ISI), two Gabors appeared for 40 ms. The 110 ms between cue and stimulus onsets ensured that participants' attention was at peak activation during the Gabor presentation and that they did not have time to execute planned eye movements before offset of the display (Jonides, 1981; Nakayama & Mackeben, 1989).

Participants were instructed to "report the orientation of the Gabor of higher spatial frequency" by pressing one of four keys: "z" (left) or "x" (right) for the left Gabor, "." (left) and "/" (right) for the right Gabor. They had 2 s to respond. These instructions emphasized the orientation judgment, when in fact we were interested in participants' spatial-frequency judgments. To minimize response bias, we did not directly ask participants about their

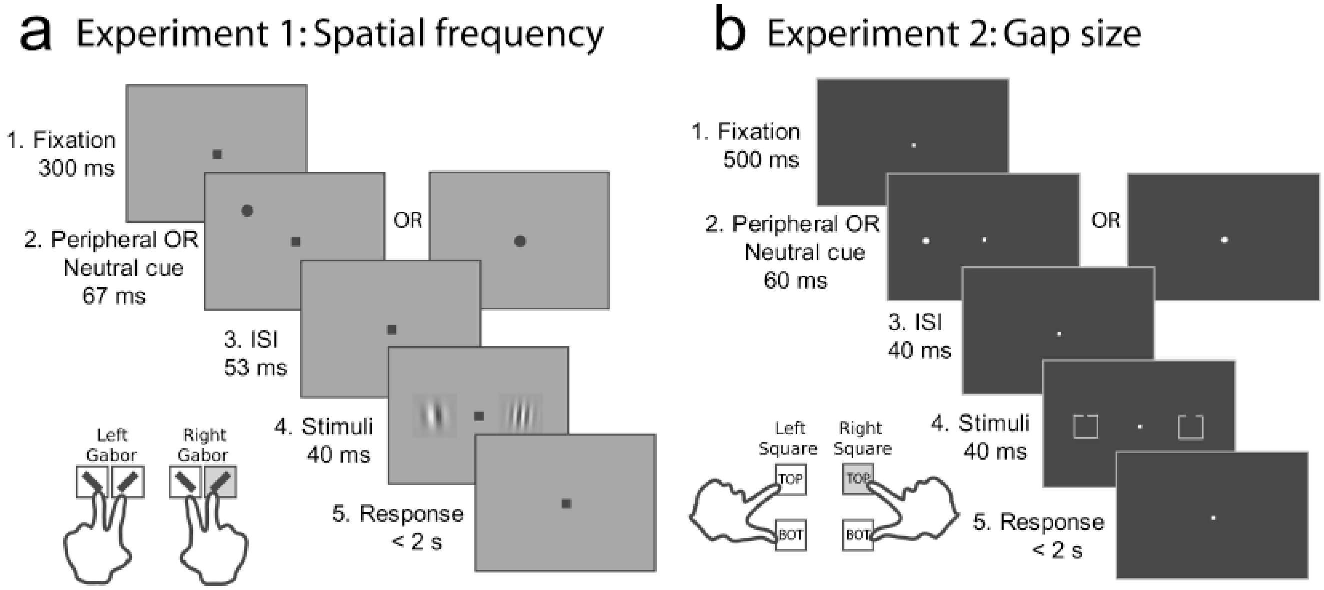

Fig. 1. Procedure for Experiment 1 (a) and Experiment 2 (b). In Experiment 1, participants were asked to report the orientation (left/right) of the Gabor of higher spatial frequency. In Experiment 2, participants were asked to report the location (top/bottom) of the gap for the square with a larger gap. Both experiments also included a postcue condition that was identical except that the stimuli and cue displays were reversed in order. The response keys appropriate for the displays shown here are highlighted in gray. ISI = interstimulus interval.

perception of frequency. Instead, their frequency perception determined which of the two orientations they reported. Participants were told that the cues provided no information as to which of the Gabors was of higher frequency or whether it was tilted to the left or right. They were explicitly instructed that if they based their response on the cue, their performance would be at chance.

We conducted three control experiments. The first two were designed to rule out the possibility that participants' judgments were biased toward the stimulus location adjacent to the cue. The third was run to verify that any observed shift in apparent spatial frequency at the cued location was not a secondary effect of a change in apparent contrast. Thus, in the first control experiment, a postcue was used instead of a precue, to remove any effect that attention might have on the perception of spatial frequency. In the second control experiment, participants reported the orientation of the Gabor of lower spatial frequency. If their responses were due to cue bias, they would still choose the cued stimulus more often than the uncued one. In the third control experiment, we eliminated cues to prevent a change in apparent contrast. Participants reported the orientation of the Gabor of higher spatial frequency while ignoring the contrast differences. The standard Gabor was always of 50% contrast, and the test Gabor varied in contrast (25–99%). Except as just noted, the stimuli and task in all three control experiments were identical to those of the main experiment.

Results and Discussion

This experiment demonstrated that attention increases apparent spatial frequency. This small but reliable shift (4–5%) was shown to be due to the deployment of attention, and not to any cue bias.

Figures 2a, 2b, and 2c all show the three psychometric functions estimated from the data: test location cued, standard location cued, and neutral cue. Each data point shows, for each test frequency, the proportion of trials on which the observer chose the test Gabor as the stimulus with higher spatial frequency. Each curve was generated by fitting a Weibull distribution, using log likelihoods to fit the corresponding set of data. The vertical lines indicate, for each condition, the point of subjective equality (PSE), the point at which the test and standard were equally likely to be reported as having higher frequency.

Figure 2a shows the data for low- and high-frequency standards in the main experiment (i.e., when precues were used). The shifts of the test-cued curves (low frequency: $p = .001$, $r = .825$; high frequency: $p < .0001$, $r = .824$) and the standard-cued curves (low frequency: $p = .004$, $r = .767$; high frequency: $p = .001$, $r = .765$) relative to the neutral-cue curves indicate an increase in apparent frequency with attention. When attention was deployed to the test Gabor, it was considered to be the same frequency as the standard (i.e., it was at the PSE) when it was physically lower in frequency than the standard. Conversely, when attention was deployed to the standard, the test was considered to be the same frequency as the standard when it was physically higher in frequency than the standard. The PSEs, expressed in terms of the difference in frequency between the test and standard (where 0 indicates the standard and test are equal in frequency), were as follows—low frequency: −0.06 cycles/deg for test cued, 0.07 cycles/deg for neutral cue, and 0.19 cycles/deg for standard cued; high frequency: −0.04 cycles/deg for test cued, 0.18 cycles/deg for neutral cue, and 0.57 cycles/deg for standard cued. The results for individual observers followed the same pattern.

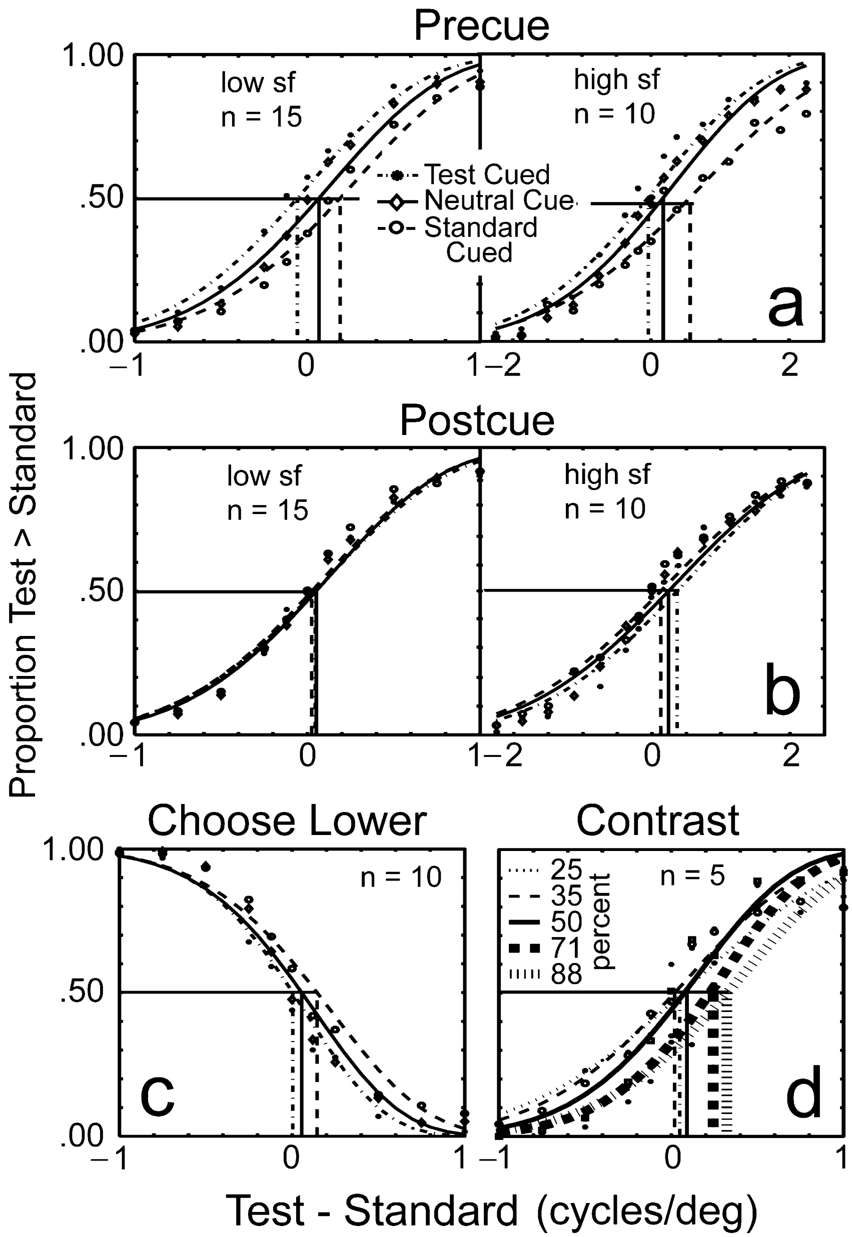

Fig. 2. Results of Experiment 1: proportion of trials on which observers chose the test Gabor as having a higher frequency than the standard Gabor, as a function of the difference between the test and standard frequencies. Results are shown separately for (a) standards with low and high frequency in the main experiment (with precue), (b) standards with low and high frequency in the control experiment in which a postcue, rather than a precue, was used, (c) the control experiment in which the orientation of the Gabor with the lower spatial frequency was reported, and (d) the control experiment in which there was no cue and the contrast of the test stimulus was manipulated. Only the low-frequency standards were used in the experiments reported in (c) and (d). Results are shown separately for the three cuing conditions (a–c) and the various Gabor contrasts presented (d). The curves are best-fit Weibull distributions. The horizontal lines at 50% indicate chance performance, and the vertical lines indicate for each condition the point of subjective equality, which is the point at which the test and standard Gabors appeared to be of the same spatial frequency. sf = spatial frequency.

Figure 2b shows the data for low- and high-frequency standards in the first control experiment (i.e., postcue instead of precue). The slight shift of the test-cued curves (low frequency: p = .738, r = .1; high frequency: p = .053, r = .5) and the standard-cued curves (low frequency: p = .071, r = .53; high frequency: p = .03, r = .55) relative to the neutral-cue curves—in the direction opposite that found in the precue condition and opposite the predicted direction—is indicative of no increase in apparent frequency due to attention (low frequency: all PSEs ~0.04 cycles/deg above the standard; high frequency: 0.37 cycles/deg for test cued, 0.24 cycles/deg for neutral cue, and 0.13 cycles/deg for standard cued). Thus, when the cue followed rather than preceded the Gabors, the shift obtained in the precue condition was eliminated.

Figure 2c shows the data for low-frequency standards in the second control experiment (i.e., when participants reported the orientation of the Gabor of lower frequency). Because observers reported the orientation of the Gabor of lower, rather than higher, frequency, the curves are decreasing, rather than increasing. The PSEs indicate that observers were less likely to choose the cued stimulus as the one that appeared to be lower in frequency when it was cued than when it was not cued (test cued vs. neutral cue: $p = .037, r = .6$; standard cued vs. neutral cue: $p = .021, r = .65$). That is, participants were not simply more likely to choose the cued Gabor than the uncued Gabor—the cued Gabor appeared higher in frequency (PSEs: 0.06 cycles/deg for neutral cue, 0.005 cycles/deg for test cued, 0.15 cycles/deg for standard cued). In addition to ruling out a cue bias, these results address the concern that participants could have been more confident about the frequency or orientation of the cued than the uncued Gabor, and that this confidence translated into an increased tendency to choose it.

In the precue (Figs. 2a and 2c) and postcue (Fig. 2b) conditions, the Gabors were displayed at 50% contrast. Numerous studies have shown that both frequency and orientation discrimination thresholds are unaffected by contrast level at contrasts above 20% (Caelli, Brettel, Rentschler, & Hilz, 1983; Regan, Bartol, Murray, & Beverley, 1982; Regan & Beverley, 1985; Skottun, Bradley, Sclar, Ohzawa, & Freeman, 1987).

Figure 2d shows the data from the third control experiment (i.e., no cues, contrast of the test Gabor varied). In this graph, each psychometric function corresponds to a different contrast of the test Gabor. The shifts in the curves indicate that as the test Gabor increased in contrast, it was less likely to be considered higher in frequency than the standard; thus, the shift was in the direction opposite to the shift found with attention. If anything, any secondary effect of a change in apparent contrast may cause an underestimation of the shift in frequency produced by attention in the precue condition. These results rule out the possibility that the shift in spatial frequency observed in the main experiment was a secondary effect of the change in apparent contrast. Moreover, Georgeson (1985) reported that apparent spatial frequency is independent of contrast across a wide range of contrasts.[1]

Accuracy in the orientation discrimination task was very high, approximately 90% across conditions. The high accuracy and lack of difference in accuracy between the cuing conditions were expected, as the Gabors were of a high contrast (50%), for which a 5° tilt is easily discriminable.

These results differ from those of Prinzmetal, Amiri, Allen, and Edwards (1998), who found that *sustained* attention did not shift the mean apparent spatial frequency, but merely reduced the variance of the estimates. Those results may reflect the impact of general attentional load on memory, rather than the effects of covert spatial attention on perceived frequency. In the experiment of Prinzmetal et al., the stimulus location was chosen randomly (left or right), a concurrent task was used to manipulate attentional load, and the perceived-frequency judgment was based on a memory of the stimulus.

EXPERIMENT 2: GAP SIZE

This experiment investigated the effect of attention on another aspect of spatial resolution: gap size. The logic, general procedure, and data analysis were the same as in Experiment 1. Differences are detailed in the Method section. Given that attention increases both spatial resolution (e.g., Carrasco et al., 2002; Yeshurun & Carrasco, 1998, 2000) and apparent spatial frequency (Experiment 1), we predicted that it also increases apparent gap size.

Method

Participants

Twenty-nine observers participated in this experiment; 1 participated in both the precue and the postcue conditions, and the others were equally divided between the two conditions. Four were experienced psychophysical observers; 2 were not naive.

Apparatus

The apparatus was the same as in Experiment 1, except that an attenuator was not used.

Stimuli

The stimulus sequence is illustrated in Figure 1b; it was very similar to that of Experiment 1. The luminance of the white stimuli was approximately 88.5 cd/m^2, and the black background was approximately 0.01 cd/m^2.

The fixation display was a white square (0.2° × 0.2°) at the center of the screen. The cue was a white circle (0.5° in diameter) and appeared either directly at fixation (neutral cue) or centered at 4.5° eccentricity to the left or right of fixation (peripheral cue), on the horizontal meridian. As in Experiment 1, the cue was uninformative.

The Landolt-square display contained the fixation square and two Landolt squares (outlined squares, each with a gap in either the top or bottom side; 1° × 1°). The squares were centered at 3.5° eccentricity to the left and right of fixation, on the horizontal meridian. On each trial, the gap in one of the squares was the

[1]The difference between the results obtained here (Fig. 2d) and those reported by Georgeson (1985) mostly likely stem from the different contrast ranges tested. Georgeson investigated 2% through 32% contrast, whereas our contrast values were 25%, 35%, 50%, 71%, and 99%. In fact, the curves for 25% and 35% in our control experiment are very similar to each other, and more similar to the 50% curve than are the curves for 71% and 99% contrast.

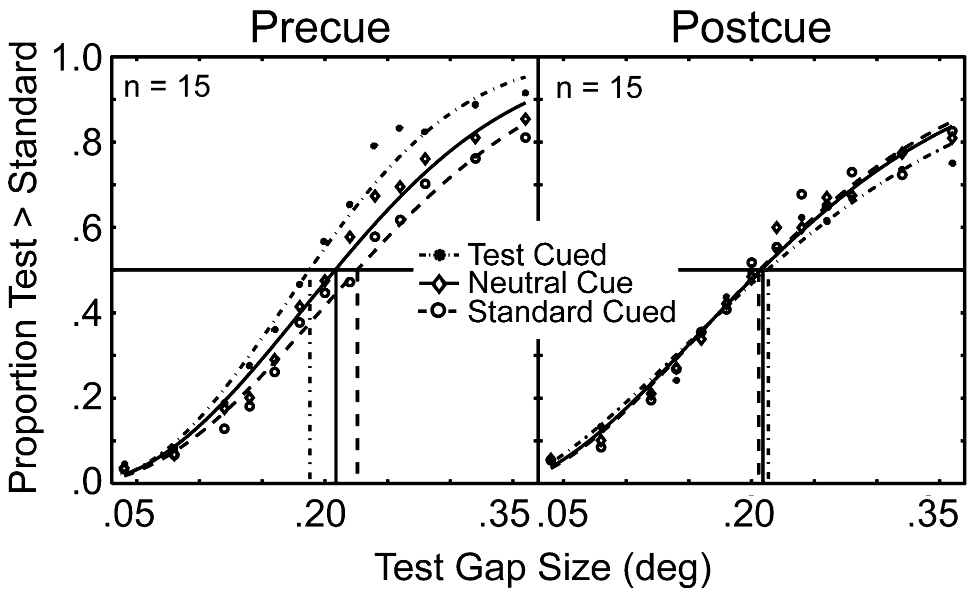

Fig. 3. Results from the precue (left) and postcue (right) conditions in Experiment 2: proportion of trials on which observers chose the test gap as being larger than the standard gap, as a function of the size of the test gap. Results are shown separately for the three cuing conditions. The curves are best-fit Weibull distributions. The horizontal lines indicate chance performance, and the vertical lines indicate for each cuing condition the point of subjective equality, which is the point at which the test and standard gaps appeared to be of the same size.

standard size of 0.2°, and the gap in the other square was a test size chosen from 13 values ranging around the standard gap size from 0.04° to 0.36°.

Procedure

Participants performed 50 practice and 1,500 experimental trials, at a viewing distance of 114 cm. The sequence of events in a trial was very similar to that of Experiment 1 (see Fig. 1b), but the timing differed slightly: 500-ms intertrial interval, 60-ms cue, 40-ms ISI, and 40-ms Landolt-square display.

Participants were instructed to "report the location of the gap for the square with the larger gap," by pressing one of four keys: "a" (top) or "z" (bottom) for the left square, "k" (top) or "m" (bottom) for the right square. These instructions emphasized the location of the gap, when in fact we were interested in participants' judgments regarding gap size. We did not ask participants directly about their perception of gap size, in order to minimize the possibility of response bias. Instead, their perception of gap size determined which of the two stimuli they chose to report on. Participants were told that basing their response on the cue would result in chance performance.

To control for cue bias, we also ran a postcue condition that was identical to the precue condition in every way except that the cue was presented after the Landolt squares rather than before; this sequence removed any effect that attention might have on the appearance of gap size.

Results and Discussion

Attention increased apparent gap size, and this shift was due to the deployment of attention, not to cue bias—when the cue followed instead of preceded the squares, no shift in apparent size was found.

Figure 3 displays the data, using the same conventions as in Figure 2. The left-hand panel shows the data for the precue condition. The shifts of the test-cued and standard-cued curves relative to the neutral-cue curve are indicative of an increase in apparent gap size with attention (test cued vs. neutral cue: $p < .0001$, $r = .84$; standard cued vs. neutral cue: $p < .0001$, $r = .83$). When attention was deployed to the test square, its gap was considered equal in size to the standard gap (i.e., at the PSE) when it was physically smaller (0.18°) than the standard (0.20°). Conversely, when attention was deployed to the standard square, the test gap was considered equal in size to the standard gap when it was larger than the standard (0.23°). When attention was deployed to neither square, the test gap was considered equal in size to the standard gap when it was in fact approximately equal in size (0.21°) to the standard. The data for individual observers followed a similar pattern.

The observed shift in apparent gap size is similar to the change in gap-size threshold obtained in previous studies (see Fig. 5b of Carrasco et al., 2002,and Fig. 3b of Yeshurun & Carrasco, 1999). In those studies, the gap size required for 75% accuracy in gap detection was approximately 0.02° smaller when a precue appeared at the stimulus location than when there was a neutral cue.

The right-hand panel of Figure 3 shows the data for the postcue condition. The lack of any shift of the test-cued and standard-cued curves relative to the neutral-cue curve (test cued vs. neutral cue: $p = .24$, $r = .34$; standard cued vs. neutral cue: $p = .81$, $r = .07$) is indicative of no change in apparent gap size associated with the postcue (all PSEs $\sim 0.21°$).

The high accuracy in reporting the location of the gap (97%) and the lack of difference in accuracy between the cuing conditions were expected, as the vast majority of gap sizes used were far above gap thresholds at the tested eccentricity (~0.05°).

GENERAL DISCUSSION

These experiments provide clear evidence that attention increases apparent spatial frequency and apparent gap size, which are both related to spatial resolution. The magnitude of these changes is illustrated in Figure 4. Our predictions that attention would increase both apparent spatial frequency and apparent gap size were based on experiments showing that attention increases spatial resolution (Balz & Hock, 1997; Tsal & Shalev, 1996; Yeshurun & Carrasco, 1998, 2000) and acuity (Carrasco et al., 2002; Shalev & Tsal, 2002; Yeshurun & Carrasco, 1999).

A possible neural correlate for enhanced spatial resolution is suggested by studies showing that attention increases spatial resolution by contracting a neuron's effective receptive field around the attended stimulus (Luck, Chelazzi, Hillyard, & Desimone, 1997; Reynolds & Chelazzi, 2004; Reynolds & Desimone, 1999). This increase in resolution allows neurons with multiple stimuli inside their receptive fields to selectively process the attended stimulus by effectively placing an unattended stimulus outside of the shrunken receptive field.

Researchers have developed models in which the effect of attention on spatial resolution plays an important role. For instance, in a neuronal model of object recognition, "attention control decides iteratively in which local regions the spatial resolution should be enhanced" (Deco & Zihl, 2001, p. 233). In a computational model of how attention alters visual perception, attention activates a winner-take-all competition between overlapping visual spatial filters, and the effects of attention on visual cortical neurons include sharper tuning to spatial frequency, in addition to increased contrast gain and sharper orientation tuning (Lee, Itti, Koch, & Braun, 1999).

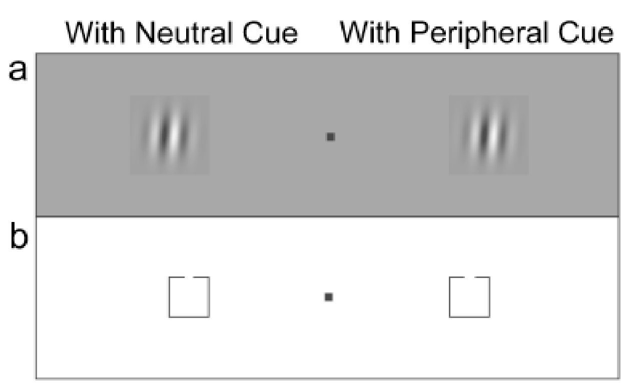

Fig. 4. **Illustration of the effect of attention on appearance, scaled to a viewing distance of 57 cm: (a) shift in apparent spatial frequency (3.5 cycles/deg with neutral cue, 3.68 cycles/deg with peripheral cue) and (b) shift in apparent gap size (0.20° with neutral cue, 0.23° with peripheral cue).**

We propose a straightforward way, based on known mechanisms, in which attention might increase apparent spatial frequency: In the absence of attention, a stimulus of a particular spatial frequency will produce a particular pattern of differential activity in different channels. If attention shifts sensitivity to higher spatial frequencies (Ho et al., 2002; Yeshurun & Carrasco, 2000), the sensitivity of those channels will increase (perhaps the sensitivity of the lower spatial-frequency channels will decrease, though this is not necessary), producing a different pattern of activity for this same stimulus. The pattern under the influence of attention will be consistent with a pattern that would be observed in the absence of attention if the stimulus were of a higher spatial frequency. This would result in the phenomenological experience of a higher spatial frequency.

Several studies suggest a mechanism whereby attention may induce an increase in apparent gap size. Attention has been shown to decrease estimations of line length (Tsal & Shalev, 1996) and to improve gap localization in line stimuli (Shalev & Tsal, 2002). These authors suggested that the best account of their effects is that attention increases resolution and thereby alters perceived distance between the two ends of the line stimuli. In the line-length estimation, attention decreases the perceived distance between the two ends of the single line stimulus. In the gap-localization task, attention increases the perceived distance between the ends of the two line stimuli—it makes the gap bigger, thereby easier to localize. This explanation is consistent with Ginsburg's (1984) explanation of length illusions. In a low-pass filtered image of the Müller-Lyer illusion, but not in a high-pass filtered image, the inward arrowheads cause the horizontal line segments to be physically shorter than do the outward arrowheads. Carrasco, Figueroa, and Willen (1986) provided psychophysical evidence for this account by demonstrating that selective adaptation to low—but not high—spatial frequencies reduces the magnitude of the illusion. In the Landolt-square stimulus, the perceived size of the gap is determined by the perceived length of the line segments on both sides of the gap. Attention increases spatial resolution, which is mediated by higher spatial frequencies, providing a more precise estimate of the location of the ends of the line segments. This diminishes the estimation errors produced without attention, thereby producing the appearance of a larger gap.

To conclude, this study provides further evidence that it is possible to objectively and quantitatively study the effects of attention on subjective experience. In addition to allowing for prioritization and improvement of early visual processing, attention actually alters one's experience of the visual world.

Acknowledgments—This work was supported by National Science Foundation Grant BCS-9910734 to M.C. and by National Institutes of Health Grant MH 19524. We thank New York University undergraduates R. Kothari and J. Fulton for their assistance with data collection, and the members of the Carrasco lab for their helpful comments.

REFERENCES

Baldassi, S., & Burr, D.C. (2000). Feature-based integration of orientation signals in visual search. *Vision Research*, *40*, 1293–1300.

Balz, G.W., & Hock, H.S. (1997). The effect of attentional spread on spatial resolution. *Vision Research*, *37*, 1499–1510.

Brainard, D.H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.

Caelli, T., Brettel, H., Rentschler, I., & Hilz, R. (1983). Discrimination thresholds in the two-dimensional spatial frequency domain. *Vision Research*, *23*, 129–133.

Cameron, E.L., Tai, J.C., & Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity. *Vision Research*, *42*, 949–967.

Carrasco, M., Figueroa, J.G., & Willen, J.D. (1986). A test of the spatial-frequency explanation of the Muller-Lyer illusion. *Perception*, *15*, 553–562.

Carrasco, M., Giordano, A.M., & McElree, B. (2004). Temporal performance fields: Visual and attentional factors. *Vision Research*, *44*, 1351–1365.

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

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences, USA*, *98*, 5363–5367.

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

Carrasco, M., Williams, P.E., & Yeshurun, Y. (2002). Covert attention increases spatial resolution with or without masks: Support for signal enhancement. *Journal of Vision*, *2*, 467–479.

Deco, G., & Zihl, J. (2001). A neurodynamical model of visual attention: Feedback enhancement of spatial resolution in a hierarchical system. *Journal of Computational Neuroscience*, *10*, 231–253.

Foley, J.M., & Schwartz, W. (1998). Spatial attention: Effect of position uncertainty and number of distractor patterns on the threshold-versus-contrast function for contrast discrimination. *Journal of the Optical Society of America*, *15*, 1036–1047.

Georgeson, M.A. (1985). Apparent spatial frequency and contrast of gratings: Separate effects of contrast and duration. *Vision Research*, *25*, 1721–1727.

Ginsburg, A.P. (1984). Visual form perception based on biological filtering in sensory experience, adaptation, and perception. In L. Spillman & B.R. Wooten (Eds.), *Sensory experiences, adaptation, and perception* (pp. 53–72). Hillsdale, NJ: Erlbaum.

Gurnsey, R., Pearson, P., & Day, D. (1996). Texture segmentation along the horizontal meridian: Nonmonotonic changes in performance with eccentricity. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 738–757.

Ho, Y.-X., Loula, F., & Carrasco, M. (2002). Attention enhances spatial resolution by shifting sensitivity to high spatial frequencies. *Journal of Vision*, *2*, Abstract 449. Retrieved from http://www.journalofvision.org/2/7/449/

Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J.B. Long & A.D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–204). Hillsdale, NJ: Erlbaum.

Lee, D.K., Itti, L., Koch, C., & Braun, J. (1999). Attention activates winner-take-all competition among visual filters. *Nature Neuroscience*, *2*, 375–381.

Lu, Z., & Dosher, B.A. (1998). External noise distinguishes attention mechanisms. *Vision Research*, *38*, 1183–1198.

Luck, S.J. (2004). Understanding awareness: One step closer. *Nature Neuroscience*, *7*, 208–209.

Luck, S.J., Chelazzi, L., Hillyard, S.A., & Desimone, R. (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *Journal of Neurophysiology*, *77*, 24–42.

Morgan, M.J., Ward, R.M., & Castet, E. (1998). Visual search for a tilted target: Tests of spatial uncertainty models. *Quarterly Journal of Experimental Psychology A*, *51*, 347–370.

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

Pelli, D.G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.

Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of attention: 1. Color, location, orientation, and spatial frequency. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1–22.

Regan, D., Bartol, S., Murray, T.J., & Beverley, K.I. (1982). Spatial frequency discrimination in normal vision and in patients with multiple sclerosis. *Brain*, *105*, 735–754.

Regan, D., & Beverley, K.I. (1985). Postadaptation orientation discrimination. *Journal of the Optical Society of America*, *2*, 147–155.

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

Reynolds, J.H., Chelazzi, L., & Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *Journal of Neuroscience*, *19*, 1736–1753.

Reynolds, J.H., & Desimone, R. (1999). The role of neural mechanisms of attention in solving the binding problem. *Neuron*, *24*, 19–29.

Shalev, L., & Tsal, Y. (2002). Detecting gaps with and without attention: Further evidence for attentional receptive fields. *European Journal of Cognitive Psychology*, *14*, 3–26.

Skottun, B.C., Bradley, A., Sclar, G., Ohzawa, I., & Freeman, R.D. (1987). The effects of contrast on visual orientation and spatial frequency discrimination: A comparison of single cells and behavior. *Journal of Neurophysiology*, *57*, 773–786.

Solomon, J.A., Lavie, N., & Morgan, M.J. (1997). Contrast discrimination function: Spatial cuing effects. *Journal of the Optical Society of America*, *14*, 2443–2448.

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

Tsal, Y., & Shalev, L. (1996). Inattention magnifies perceived length: The attentional receptive field hypothesis. *Journal of Experimental Psychology*, *22*, 233–243.

von Berg, J., Ziebell, O., & Stiehl, H.S. (2002). Texture segmentation performance related to cortical geometry. *Vision Research*, *42*, 1917–1929.

Yeshurun, Y., & Carrasco, M. (1998). Attention improves or impairs visual performance by enhancing spatial resolution. *Nature*, *396*, 72–75.

Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research*, *39*, 293–306.

Yeshurun, Y., & Carrasco, M. (2000). The locus of attentional effects in texture segmentation. *Nature Neuroscience*, *3*, 622–627.

(Received 7/20/04; Accepted 8/31/04)