Transient covert attention and the perceived rate of flicker

Barbara Montagna
Department of Psychology, New York University, New York, NY, USA

Marisa Carrasco
Department of Psychology and Center for Neural Science, New York University, New York, NY, USA

Transient covert attention affects basic visual dimensions such as contrast sensitivity, spatial resolution, and temporal resolution. Two recent studies provide evidence of corresponding phenomenological changes: The increase in contrast sensitivity and spatial resolution at the attended location is associated with increased apparent contrast (M. Carrasco, S. Ling, & S. Read, 2004) and apparent spatial frequency (J. Gobell & M. Carrasco, 2005). Here, we assessed a phenomenological correlate of attention for temporal vision, asking whether and how transient attention affects perceived flicker rate. We employed a psychophysical method developed to assess changes in appearance by manipulating transient attention via uninformative spatial cues. In each trial, two suprathreshold Gabor stimuli, appearing briefly to the left and right of fixation, were counterphase modulated at either the same or different temporal frequencies. To assess appearance, we asked observers to perform an orientation discrimination task contingent on perceived flicker rate: ''What was the orientation of the Gabor that flickered faster?'' Results indicated that perceived flicker rate increased at the cued location. A control experiment, in which observers reported the orientation of the Gabor that flickered slower, ruled out a cue bias explanation. We conclude that transient attention increases perceived flicker rate.

Keywords: attention, appearance, temporal vision, flicker rate

Introduction

The phenomenology of selective attention

Selective attention affects performance on a remarkable variety of visual tasks. Psychophysical research has established that when observers are cued to selectively attend to a specific region of their visual field, they are faster and more accurate at detecting, discriminating, and identifying visual stimuli in that region compared with unattended regions (for reviews, see, e.g., Kinchla, 1992; Pashler, 1998; Sperling & Dosher, 1986; van der Heijden, 1992). But does attention correspondingly change the observers' subjective experience of visual stimuli on which they are performing the tasks? Is our visual experience altered when we selectively attend to a given stimulus compared with when we do not?

The issues of whether and how selective attention can affect the phenomenology of vision and which aspects of our visual experience it may change have long intrigued philosophers, psychologists, psychophysicists, and neurophysiologists but are still questions under debate. Can attending to a visual pattern make it look more detailed, or a light more intense, than they otherwise would? Can attention affect the vividness of the colors we experience? Can attention make us experience a light to be fluctuating at a different rate? Here, we ask whether attention affects perceived flicker rate.

Notwithstanding strong empirical evidence that attention affects performance on visual tasks and considerable advances in our understanding of visual attention and its underlying mechanisms (Baldassi, Burr, Carrasco, Eckstein, & Verghese, 2004; Itti, Rees, & Tsotsos, 2005), the issue as to whether and how attention affects appearance has not been investigated systematically until recently (e.g., Carrasco, Ling, & Read, 2004; Gobell & Carrasco, 2005; Prinzmetal, Amiri, Allen, & Edwards, 1998; Tsal & Shalev, 1996; Tsal, Shalev, Zakay, & Lubow, 1994; Tse, 2005). This discrepancy may be ascribed to the difficulty of testing and objectively quantifying the subjective experience of perceived stimuli and a possible change in such experience with attention (e.g., James, 1890/1950; Luck, 2004). The phenomenology of selective attention has been a subject of debate among pioneer investigators in experimental psychology and psychophysics such as Mach, Fechner, von Helmholtz, Wundt, and James (for a review of such debate, see James, 1890/1950; Wundt, 1902). Much of this early work was introspective in character, and often, opposite conclusions were drawn from such subjective method of investigation. James (1890/1950) describes the disagreement among investigators about whether attention increases the perceived intensity of a stimulus and concludes: "The subject

doi: 10.1167/6.9.8 Received April 7, 2006; published August 18, 2006 ISSN 1534-7362 © ARVO

is one which would well repay exact experiment, if methods could be devised" (p. 426).

Recently, a new psychophysical paradigm was developed in our laboratory, which allows for a more objective assessment of whether and how transient attention changes the subjective experience of perceived stimuli (Luck, 2004; Treue, 2004). This paradigm has been used to evaluate the effects of attention on spatial visual dimensions, namely, perceived contrast (Carrasco, Ling, et al., 2004), spatial frequency (Gobell & Carrasco, 2005), and color saturation and hue (Fuller & Carrasco, in press). In this study, we adapted this paradigm to a temporal perception task to explore attentional effects on the apparent temporal frequency of flickering stimuli.

Transient covert attention affects both performance and appearance of spatial vision

Spatial attention allows us to select information at a given location in our visual field, for privileged processing. Whereas we typically foveate to the locations in space to which we attend, we can direct our attention to regions in our visual field without moving our gaze toward those locations (e.g., Eriksen & Hoffman, 1972; James, 1890/1950; Posner, 1980; von Helmholtz, 1910/1925; Wundt, 1902). This orienting of attention in space in the absence of eye movements is referred to as spatial covert attention (Posner, 1980). It can be allocated to a certain region of the visual field either voluntarily—sustained or endogenous attention—or in a reflexive manner, in response to sudden stimulation in that region—transient or exogenous attention.

Studies that have manipulated transient attention have shown that it affects basic spatial dimensions of vision, such as contrast sensitivity (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Ling & Carrasco, 2006; Lu & Dosher, 1998; Pestilli & Carrasco, 2005), spatial resolution (Talgar & Carrasco, 2002; Yeshurun & Carrasco, 1998, 2000), and acuity (Carrasco, Williams & Yeshurun, 2002; Golla, Ignashchenkova, Haarmeier, & Their, 2004; Mackeben & Nakayama, 1993; Yeshurun & Carrasco, 1999). Correspondingly, transient attention changes appearance along these spatial dimensions. It increases the perceived contrast of the attended stimulus (Carrasco, Ling, et al., 2004). Similarly, attention increases perceived spatial frequency and gap size (Gobell & Carrasco, 2005).

The perception of flicker

The information for vision is light distributed over space and time. In general, more is known about spatial than temporal vision, as well as about the effects of attention on spatial than on temporal aspects of vision. Flickering stimuli have been traditionally used to estimate observers' sensitivity to temporal changes in luminance and contrast (Watson, 1986) and to explore what factors affect apparent flicker rate (e.g., Thompson & Stone, 1997). Here, we explored whether and how attention affects the apparent temporal frequency of flickering stimuli. Can transient attention either increase or decrease the apparent rate of flicker?

Our knowledge of temporal aspects of human vision derives primarily from threshold studies that have measured the temporal contrast sensitivity and critical flicker frequency. Other studies with suprathreshold stimuli have shown that perceived temporal frequency varies continuously with physical frequency, at least up to 10 Hz (Fukuda, 1977). Perceived flicker rate is affected by the amplitude of temporal modulations (as the depth of the modulation increases, perceived flicker rate decreases; Bowker, 1982; Thompson & Stone, 1997) and by the spatial frequency of the stimulus (as the spatial frequency of the modulated stimuli increases, apparent flicker rate increases; Bowker, 1982). In the Discussion section, we will address how these factors may be relevant for this study.

Experiment 1: Does transient attention affect perceived flicker rate?

A number of behavioral studies provide evidence of effects of transient attention on performance in temporal vision, for example, temporal resolution (Yeshurun & Levy, 2003) and temporal order discrimination (Hein, Rolke, & Ulrich, 2006; Shore, Spence, & Klein, 2001), as well as on the temporal dynamics of processing (Carrasco, Giordano, & McElree, 2004, 2006; Carrasco & McElree, 2001).

Here, we explored whether transient attention affects appearance of a temporal aspect of vision. Specifically, we investigated whether and how transient covert attention affects the perceived rate of flicker of temporally modulated stimuli. To do so, we employed a paradigm designed to assess phenomenological correlates of attention (Carrasco, Ling, et al., 2004; Gobell & Carrasco, 2005). We manipulated transient attention via spatial cues and measured appearance psychometric functions. The spatial cues were presented briefly adjacent to the target location. These cues are assumed to automatically draw the observer's attention to such location. Their effect is transient; it peaks at about 120 ms and decays rapidly (e.g., Carrasco, Ling, et al., 2004; Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Yantis & Jonides, 1984). Observers saw two simultaneous flickering Gabors (a standard Gabor of fixed temporal frequency and a test Gabor whose temporal frequencies were distributed around the standard). In this experiment, observers were instructed to indicate the orientation of the Gabor stimulus that flickered *faster*.

Methods

Observers

Eleven observers participated in the experiment. All observers had normal or corrected-to-normal vision. The New York University Committee on Activities Involving Human Subjects approved the experimental protocol.

Apparatus

Stimulus presentation and data collection were controlled by a Macintosh G4 computer attached to a gamma-corrected 21-in. (diagonal) "CTX PR 1400 F" CRT monitor, on which stimuli were displayed. The monitor resolution was set to 1,024 × 768 pixels at a frame rate of 120 Hz. Background luminance was set to 39 cd/m^2. Participants viewed the monitor binocularly from a distance of 57 cm. A chin rest was used to stabilize their head position and maintain the viewing distance. Stimuli were generated and presented using Matlab and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Eye movements were monitored via an iScan infrared camera to ensure that observers did not break fixation.

Stimuli and procedure

The experimental procedure was adapted from the study of Carrasco, Ling, et al. (2004). On each trial, observers were presented with a simultaneous pair of Gabors, appearing on the right and left of fixation and independently oriented either to the left or to the right. The two Gabors were counterphase modulated either at the same or at different rates. The observers' task was to report the orientation of the Gabor that flickered faster. The Gabors were preceded by either a *neutral cue,* appearing at the center of the screen, or a *peripheral cue,* appearing adjacent to one of the two subsequent Gabors' locations.

Each trial sequence began with the presentation of a fixation point (0.1 deg in diameter) at the center of the screen (Figure 1a). Observers were instructed to keep their eyes fixated on that point throughout the trial. Next, a cue (a white disk of 0.3 deg in diameter) was presented for 20 ms. On each trial, the cue was either "neutral" or "peripheral." The neutral cue appeared at the center of the screen, superimposed on the fixation point. The peripheral cue appeared adjacent to the location of one of the two subsequent Gabors (1.5 deg into the periphery from the center of the region where one of the Gabors was about to appear, on the horizontal meridian). Both types of cues indicated the onset of the flickering Gabors (Jonides & Mack, 1984). Yet, only the

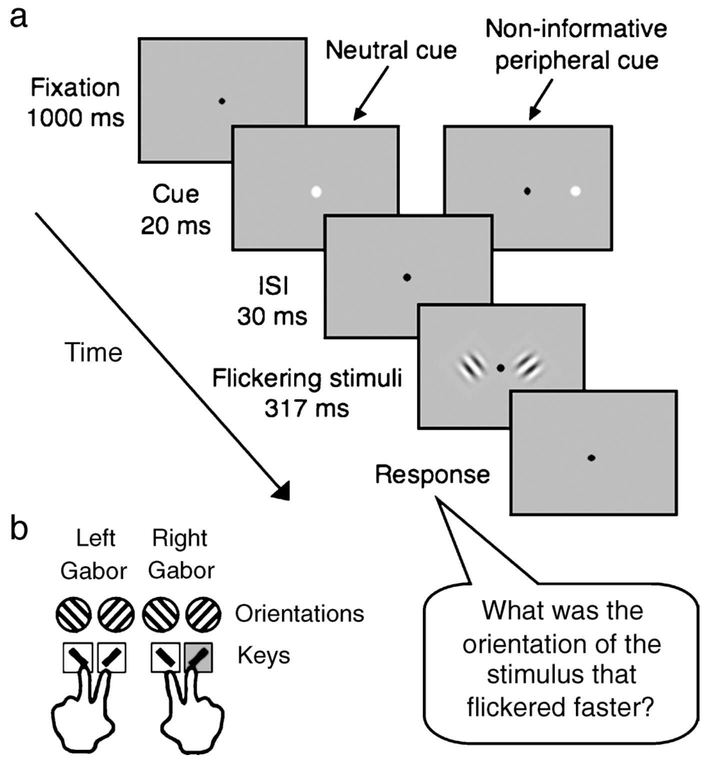

Figure 1. A typical trial. (a) Sequence and duration of events in a typical trial. Observers kept their eyes on a fixation point throughout the trial. A neutral cue, appearing at fixation, or a noninformative peripheral cue, appearing adjacent to one of two subsequent Gabor stimuli's location, was presented. After an ISI, two counterphase modulated Gabor stimuli (standard and test) appeared to the right and to the left of fixation. Observers performed an orientation discrimination task contingent upon perceived flicker rate, reporting the orientation of the Gabor stimulus that flickered faster. (b) To indicate their response, observers used the hand corresponding to the side of the Gabor stimulus that they had perceived to flicker faster. In this example, the observer perceived the right Gabor to flicker faster and reported its orientation with the right hand by pressing the key highlighted in gray.

peripheral cue automatically drew the observer's attention to one of the locations at which the flickering Gabors were about to appear. The peripheral cue was not predictive of either the orientation or the temporal frequency of the Gabors; thus, observers could not rely on its presence to give their response. After an interstimulus interval (ISI) of 30 ms, the target display was presented. Two Gabor patches appeared simultaneously on the right and left sides of fixation along the horizontal meridian (each Gabor's center at 1.5 deg of eccentricity). Their size was 2 deg in diameter; their center spatial frequency was 2 cycles per degree (cpd), and their contrast was 26.5% (Michelson contrast).

In each trial, the simultaneously presented Gabors varied independently in orientation: They were tilted either to the right or to the left (±15 deg off vertical).

The two Gabors were square wave counterphase modulated at either the same or different temporal frequencies for 317 ms. One of the two Gabor patches (standard Gabor) was always modulated at 7.5 cycles/s (Hz). Using the method of constant stimuli, the temporal frequency of the other Gabor patch (test Gabor) varied randomly on each trial: 3.75, 4.62, 6, 7.5, 8.57, 10, or 12 Hz. When the temporal frequencies of the test and standard were the same, the phase of their modulations was constrained to be unequal, to prevent them from standing out, based on synchronous modulation. The randomization of the flicker rates and of the location of the standard and test stimuli prevented systematic adaptation effects.

Observers performed a two-by-two alternative forced-choice task: At the end of each trial, they indicated the orientation of the Gabor patch that flickered faster. If the stimulus to the right of fixation appeared to flicker faster, observers reported its orientation by pressing the key corresponding to the index (oriented to the left) or middle finger (oriented to the right) of their right hand (Figure 1b). All observers had at least 72 practice trials before the beginning of data collection. Each observer completed 1,344 experimental trials.

To minimize response bias the experimental paradigm emphasized to the observers the orientation discrimination task, when in fact, we were interested in their judgments about flicker rate. Furthermore, to prevent cue bias, that is, the tendency of the observer to choose the Gabor patch that is preceded by the peripheral cue, and to prevent observers from assigning more weight to information extracted at the cued location (Kinchla, 1992), we told observers that the peripheral cue was not informative with reference to either the flicker rate or the orientation of the stimuli and that it appeared equally often next to either the Gabor that flickered faster or the one that flickered slower.

The size, eccentricity, and spatial frequency of the Gabor patches were chosen to be similar to the stimuli used by Thompson and Stone (1997), who have shown that observers are able to reliably discriminate flicker rates for short stimulus durations (500 ms). The effect of transient attention on performance has been estimated to peak at around 120 ms after the onset of the cue and to decay rapidly such that it extinguishes completely after around 300 ms (e.g., Cheal & Lyon, 1991; Jonides, 1981; Nakayama & Mackeben, 1989). Given this transient nature, it was crucial to use target displays of short duration. However, for a flicker rate to be perceived, we had to employ a target display duration (317 ms) longer than typically used with this cueing paradigm. Thus, the SOA between the spatial cue and the flickering Gabors was reduced (cue = 20 ms, ISI = 30 ms). We used temporal frequencies that ensured that at least two cycles of modulation would occur within the brief train of flicker. The upper limit of the chosen range of temporal frequencies was based on the finding that perceived flicker varies in proportion with physical temporal frequency up to about 10 Hz but then asymptotes (Fukuda, 1977). Moreover, given that apparent depth of modulation of suprathreshold flicker is proportional to temporal contrast detection threshold (e.g., Marks, 1970), to prevent observers from discriminating Gabor stimuli based on their apparent depth of modulation (Mandler, 1984), rather than their apparent flicker rate, we used a range of flicker rates corresponding to a relatively flat portion of the temporal contrast sensitivity function (e.g., Robson, 1966).

Results

Observers indicated the orientation[1] of the test or standard Gabor that appeared to flicker faster. Appearance results were plotted as psychometric functions, representing the proportion of trials in which the test stimulus was perceived as flickering faster than the standard stimulus (of fixed temporal frequency = 7.5 Hz), as a function of the physical temporal frequency of the test (ranging from 3.75 to 12 Hz). All data were collapsed across cue location (left or right hemifield) and stimulus location (left or right hemifield). Given the fact that observers maintained fixation in >99% of the trials, all trials were included in the data analysis.[2]

Weibull functions (Weibull, 1951) with two free parameters—the location parameter α and the slope parameter β—were fitted to the individual data for each cueing condition (neutral cue, test cued, and standard cued). The fitting procedure used was maximum likelihood estimation of the two parameters from the data (Wichmann & Hill, 2001). For each resulting function, the point of subjective equality (PSE) was estimated by taking the inverse of the Weibull function at a probability level of .5, corresponding to the flicker frequency of the test Gabor at which the observers' discrimination performance was at chance, that is, where the test and standard Gabors appeared to flicker at the same rate.

We computed the average of the 11 observers' responses. Three Weibull functions were fitted to the average data by the same procedure used for the individual data. The resulting estimated parameters α and β as well as the estimated PSEs are similar to the average of the individual parameters and PSEs. Psychometric functions for the average data of 11 observers are plotted in the graph in Figure 2. Compared to the neutral cue condition (central function, black continuous line), when the test stimulus is precued, a lower temporal frequency for the test is needed to match the standard. This is represented by the leftward shift of the curve (red dashed–dotted line) and its PSE. Correspondingly, when the standard stimulus is precued, the frequency of the test necessary to attain subjective equality is higher than the standard. This is represented by a rightward shift of the curve (blue dotted line) and its PSE. Thus, precueing the flickering Gabor stimuli increased their perceived temporal frequency.

To test for overall differences in the PSEs across cueing conditions (neutral cue, test stimulus cued, standard stimulus cued), we conducted a one-way repeated measures ANOVA on the individual PSEs. There was a significant effect of cueing condition, Wilks' λ = .29, $F(2,9) = 14.44$, $p < .005$, multivariate $\eta^2 = .71$. Post hoc pairwise comparisons revealed that the PSEs differed significantly among the three cueing conditions. Using the Bonferroni correction, paired-sample t tests confirmed that when the test (standard) stimulus was precued, the PSE was significantly lower (higher) than in the neutral cue condition, $p \leq .02$.

Figure 3 illustrates the magnitude and direction of the shift in estimated individual PSE for the standard and test cued conditions with reference to the neutral cue condition. For each observer, the red triangles represent the PSEs for the test cued versus the neutral cue condition; the blue diamonds represent the PSEs for the standard cued versus the neutral cue condition. Data points falling on the unit line would indicate no effect of cueing on perceived flicker rate. Data points above (below) the line represent PSEs where the temporal frequency of the test is lower (higher) than the standard in order for their perceived temporal frequency to match. This result confirms what emerged form the average data: Perceived flicker rate is increased at the precued location.

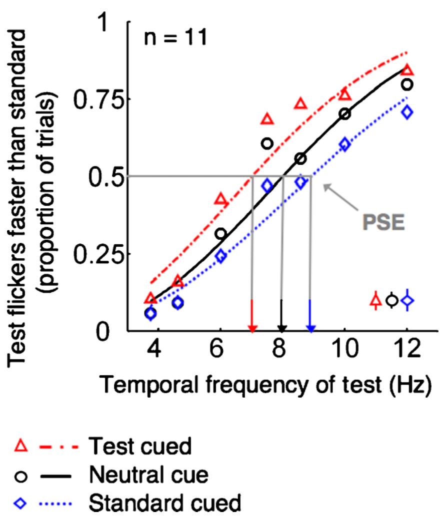

Figure 2. Precueing increases perceived flicker rate. Appearance psychometric functions for the average data (Experiment 1). Proportion of trials in which observers perceived the test stimulus to flicker faster than the standard (7.5 Hz) as a function of the temporal frequency of the test. When the test is cued (red function), the PSE occurs at lower temporal frequencies of the test, indicating that precueing increased apparent flicker rate of the test. Consistently, when the standard is cued (blue function), the PSE occurs at higher temporal frequencies of the test. The vertical arrows pointing to the abscissa indicate the PSE for each cueing condition. Average standard errors are represented for each type of cue in the lower right corner of the plot (±1 *SEM*).

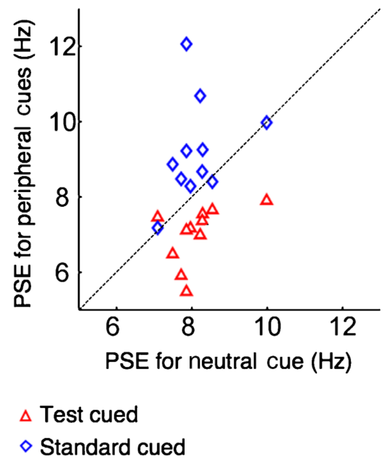

Figure 3. Individual PSEs for flicker rate. Magnitude and direction of the precueing effect on the PSEs (Experiment 1). Individual PSEs for the peripheral cue conditions as a function of the PSEs of the neutral cue condition. When the test stimulus is cued, symbols (red triangles) lie below the unit line, indicating that a lower temporal frequency of the test is needed to attain subjective equality. When the standard stimulus is cued, symbols (blue diamonds) lie above the unit line, indicating that a higher temporal frequency of the test is needed to attain subjective equality.

Experiment 2: Ruling out cue bias

It is important to rule out the possibility that cue bias—the tendency of the observer to choose the Gabor stimulus appearing at the cued location as the one flickering faster—may be responsible for an observed difference between the neutral and peripheral cue conditions (Experiment 1). Given that the cue appeared with equal probability adjacent to either of the two Gabors, responding based on the presence of the cue could not be a helpful strategy to either select the higher frequency stimulus or discriminate its orientation. Observers were explicitly told so. Notwithstanding these methodological precautions, the eleven observers who had participated in Experiment 1 participated in a control experiment to directly explore the possibility of a cue bias.

This control experiment was identical to Experiment 1, except for the instructions given to the observers. Instead of being asked to report the orientation of the Gabor that appeared to flicker *faster*, observers were asked to report the orientation of the Gabor that flickered *slower*. Had the differences between cueing conditions in Experiment 1 reflected the effects of transient attention, the results should now be exactly opposite. Results from Experiment 1 indicated that transient attention increased perceived flicker rate; when the test Gabor was cued and it had the same physical frequency as the standard, observers chose the test stimulus more often as being the stimulus that flickered faster. If transient attention indeed increases perceived flicker rate, when asked to indicate the Gabor that flickers slower, observers should now choose the cued test stimulus less frequently as being the stimulus that flickers slower. Alternatively, if results depended on cue bias, and observers thus were more likely to report the orientation of the stimulus that was cued, the observers should choose the cued stimulus regardless of the direction of the question. Reversing the direction of the question has been used as a control manipulation for this appearance paradigm (e.g., Carrasco, Ling, et al., 2004; Fuller & Carrasco, in press; Gobell & Carrasco, 2005).

Methods

Observers

The same eleven observers who had participated in Experiment 1 participated in the control experiment.

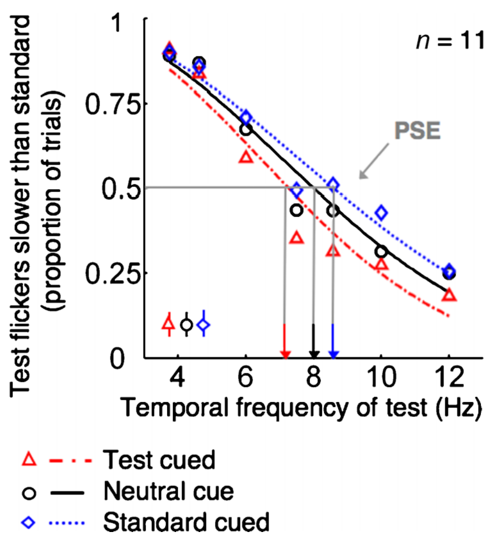

Figure 4. Precueing increases perceived flicker rate regardless of instruction. Appearance psychometric functions when observers reported the orientation of the Gabor stimulus that flickered slower (Experiment 2). Proportion of trials in which observers perceived the test stimulus to flicker slower than the standard as a function of the temporal frequency of the test. Psychometric functions are plotted for the neutral cue (black circles) and the peripheral cue conditions (test cued, red triangles; standard cued, blue diamonds). When the test is cued (red dashed–dotted function), the PSE occurs at lower temporal frequencies of the test, indicating an increase in perceived flicker rate at the cued location. Consistently, when the standard is cued (blue dotted function), the PSE occurs at higher temporal frequencies of the test. Average standard errors are represented for each type of cue in the lower left corner of the plot (±1 *SEM*).

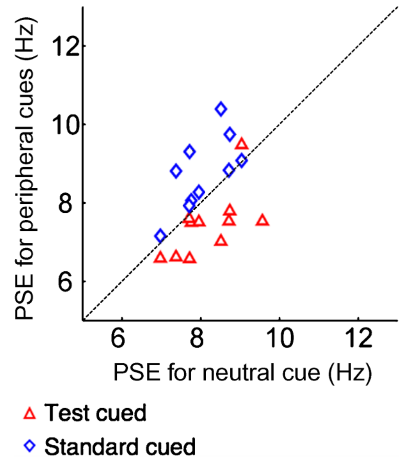

Figure 5. Individual PSEs for flicker rate. Magnitude and direction of the precueing effect on the PSEs (Experiment 2). Individual PSEs for the peripheral cue conditions as a function of the PSEs of the neutral cue condition. Deviations from the unit line indicate an effect of the peripheral precue: Data points above (below) the line represent PSEs where the temporal frequency of the test is lower (higher) than the standard in order for their perceived temporal frequency to match. When the test (standard) stimulus is cued, symbols lie below (above) the unit line, indicating that a lower (higher) temporal frequency of the test is needed to attain subjective equality.

Apparatus and stimuli

The control experiment was performed using the same apparatus and stimuli as Experiment 1.

Procedure

The procedure was identical to the ones described for Experiment 1, except for the instructions given to the observers: In the control experiment, observers were asked to report the orientation of the Gabor that flickered *slower*.

Results

Data were analyzed in the same way as in Experiment 1. Results are summarized in a graph representing average data of eleven observers[3] (Figure 4). Three Weibull functions were fitted to the average data to estimate PSEs. Compared to the neutral cue condition (central function, black continuous line), when the test stimulus was precued, the PSE was lower, as indicated by the leftward shift of the red dashed–dotted curve. Correspondingly, when the standard stimulus was precued, the PSE was higher, as illustrated by a rightward shift of the blue dotted curve.

As in Experiment 1, a one-way repeated measures ANOVA was conducted on the individual PSEs. There was a significant effect of cueing condition, Wilks' λ = .415,

$F(2,8) = 5.64$, $p < .05$, multivariate $\eta^2 = .585$. Post hoc pairwise comparisons (paired-sample t tests) confirmed that the PSE when the test (standard) stimulus was precued was significantly lower (higher) than in the neutral cue condition, $p < .025$.

Figure 5 illustrates the magnitude and direction of the shift in the individual PSEs for the standard and test cued conditions compared with the neutral cue condition. Despite the reversed instructions, perceived flicker rate is increased at the precued location: When the test (standard) stimulus is cued, symbols lie below (above) the unit line, indicating that a lower (higher) temporal frequency of the test is needed to attain subjective equality.

These results indicate that spatially precueing the flickering Gabor stimuli increased the perceived temporal frequency of their modulation, regardless of the direction of the instruction. These results are in accordance with those of Experiment 1 and rule out a cue bias explanation.

Discussion

We explored whether and how transient attention can affect our subjective experience of a dynamic stimulus, its perceived flicker rate. To do so, we used an experimental paradigm that directly assesses phenomenological correlates of attention, while ruling out cue bias (Carrasco, Ling, et al., 2004; Gobell & Carrasco, 2005). Results indicate that spatially precueing a flickering stimulus increased its perceived temporal frequency. The possible role of cue bias in determining this result was ruled out in a control experiment in which observers reported the orientation of the Gabor that flickered slower. When asked to report the orientation of the Gabor that flickered faster, observers were more likely to indicate the test patch when it was cued, showing that attention increases perceived flicker rate. Correspondingly, when asked to report the orientation of the Gabor that flickers slower, observers were less likely to indicate the test Gabor when it was precued, showing that indeed it appeared to be flickering faster. Were results determined by cue bias, observers would have chosen the test Gabor more frequently regardless of the direction of the question. We conclude that transient covert attention affects our visual experience of flicker, increasing its apparent temporal frequency. Moreover, given the fact that transient attention affects performance both at the attended and at the unattended locations—for instance, it both increases contrast sensitivity at the attended location and decreases it at the unattended location (Pestilli & Carrasco, 2005)—it is possible that in addition to increased apparent flicker rate at the attended location, a reduction of apparent flicker rate at the unattended location may have partly contributed to the present findings.

The paradigm used in this study has revealed effects of transient attention on the appearance of contrast (Carrasco, Ling, et al., 2004), spatial frequency, and gap size (Gobell & Carrasco, 2005). For these dimensions, transient attention also affects performance, contrast sensitivity (e.g., Carrasco et al., 2000), and spatial resolution (e.g., Carrasco et al., 2002). Recently, a dissociation between attention's effects on performance and appearance has been revealed. Whereas attention improves orientation discrimination performance for both hue and saturation stimuli, it alters apparent color saturation but not apparent hue (Fuller & Carrasco, in press). This dissociation provides converging evidence indicating that the reported appearance effects are not due to a cue bias, as such a bias would affect observers' response in the same manner for both dimensions.

The findings that transient covert attention increases both the apparent contrast (Carrasco, Ling, et al., 2004) and the apparent spatial frequency (Gobell & Carrasco, 2005) of attended stimuli are relevant to this study. Studies on perceived flicker rate of suprathreshold stimuli indicate that apparent temporal frequency depends on both spatial frequency (Bowker, 1982) and contrast (Bowker, 1982; Thompson & Stone, 1997) of the stimuli. Could the observed change in perceived flicker rate found here have been mediated by attentional effects on apparent spatial frequency or contrast? Perceived flicker rate increases as spatial frequency increases (Bowker, 1982). Although transient attention increases perceived spatial frequency (Gobell & Carrasco, 2005), the size of the effect (about 0.15 cpd) is 10 times smaller than the changes in spatial frequency (about 1.5 cpd) for which differences in apparent flicker rate emerge (Bowker, 1982). It is therefore implausible that the observed increase in perceived flicker rate could result merely from an increase in apparent spatial frequency. Whereas increased contrast has been found to lower the perceived flicker rate (Bowker, 1982; Thompson & Stone, 1997), here we found that attention increased perceived flicker rate. Consequently, had attention increased perceived contrast, it would have decreased perceived flicker rate. Such an effect would have diminished or counteracted the increase in perceived flicker rate observed here.

What mechanism could explain the finding that attention increases perceived flicker rate? Perceived flicker rate has been linked to the output of temporal frequency-selective channels (estimated to be 2–4 and broadly tuned; e.g., Hess & Snowden, 1992; Lehky, 1985; Pelli, 1981; Snowden & Hess, 1992; Watson & Robson, 1981), which are assumed to underlie the temporal contrast sensitivity function (Mandler, 1984; Mandler & Makous, 1984). Accordingly, the experience of a given flicker rate is related to a specific pattern of activation of labeled temporal channels, and the temporal frequency content of stimuli is coded by means of the distribution of activity across channels. This is consistent with the finding that temporal appearance is altered by temporal frequency selective adaptation, which, by attenuating the response of some channels, changes the overall distribution of activation across channels (Mandler & Bowker, 1980). Relevant to this study is the fact that temporal sensitivity increases as a function of eccentricity (Hartmann, Lachenmayr, & Brettel, 1979; Hess & Fredericksen, 2002; Snowden & Hess, 1992; Tyler, 1987) and that apparent flicker rate is overestimated in the periphery compared to the fovea for temporal frequencies below 10 Hz (Yo & Wilson, 1993). To explain their finding, Yo & Wilson (1993) proposed a model in which perceived flicker rate is determined by a weighted average of the output of three temporal frequency channels. In the periphery, the highest temporal frequency channel contributes more significantly than lower temporal frequency channels to the total output across channels.

The change in perceived flicker rate with transient attention obtained in this study could possibly result from similar differences in the pattern of activation across channels. We speculate that attention could affect the activation across temporal frequency channels by increasing the contribution of the highest temporal frequency channel to the total output; consistent with what we found here, this would result in an overestimation of perceived flicker rate in the attended compared with the neutral condition. To our knowledge, no study has directly evaluated whether transient attention selectively affects distinct temporal channels.

A mechanism similar to the one we are hypothesizing for perceived flicker has been proposed to underlie the increase in apparent spatial frequency brought about by transient attention (Gobell & Carrasco, 2005). Based on the findings that attention increases spatial resolution by shifting sensitivity to higher spatial frequencies (Carrasco, Loula, & Ho, in press) and that, in the absence of attention, a stimulus of a given spatial frequency will produce a particular pattern of differential activity in different channels (Graham, 1989), Gobell and Carrasco proposed that the change in perceived frequency brought about by attention may result from heightened sensitivity of higher spatial frequency channels, which would change the overall pattern of activity across channels, resulting in the phenomenological experience of higher spatial frequency.

The finding that transient attention speeds apparent flicker may also be related to experimental evidence suggesting faster information processing with attention. Studies employing speed–accuracy trade-off methodology show that transient attention speeds information accrual and information processing (Carrasco, Giordano, et al., 2004, 2006; Carrasco & McElree, 2001). Moreover, speed of information processing is faster at far than near eccentricity (Carrasco, McElree, Denisova, & Giordano, 2003). It has been proposed that differences in the speed of processing are partly responsible for differences in performance across eccentricities in tasks constrained by temporal sensitivity, such as temporal resolution, flicker fusion, and motion detection (Carrasco et al., 2003). Similarly, we suggest that such differences in speed of processing may underlie differences in perceived flicker as a function of eccentricity, namely, that perceived temporal frequency for frequencies below 10 Hz is overestimated at periphery compared to fovea (Yo & Wilson, 1993). We suggest that by increasing speed of processing, like eccentricity, attention may facilitate performance at tasks constrained by temporal sensitivity and speed our subjective experience of temporal changes, which would result in faster perceived flicker.

Stelmach and Herdman (1991) and Stelmach, Herdman, and McNeil (1994) have modeled how directed attention may speed the transmission of attended information by sharpening the visual system's temporal impulse response function. The temporal modulation brought about by attention is represented as the shortening of the system's activation's buildup and decay, resulting in a shorter duration of the visual signal of the attended stimulus. It has been suggested that this temporal modulation may have implications for the perception of visual stimuli that contain rapid change such as flicker (Stelmach & Herdman, 1991). With reference to the present findings, we suggest that this sharpening of the temporal response function could result in each of the events in a train of flicker being experienced brisker, which may result in an overall impression of a faster flicker rate.

Conclusion

To conclude, in this study we show a phenomenological correlate of transient attention for a temporal aspect of vision: Attention increases the apparent frequency of flicker. This study extends the observation of effects of transient attention on perceived spatial visual dimensions to the temporal domain, showing that the perceived rate of change of visual stimulation is affected by the selective allocation of attention.

Acknowledgments

We would like to thank the members of the Carrasco laboratory for their helpful comments on previous versions of the manuscript.

Commercial relationships: none.
Corresponding author: Marisa Carrasco.
Email: marisa.carrasco@nyu.edu.
Address: New York University, Department of Psychology, 6 Washington Place, New York, NY 10003-6634, USA.

Footnotes

[1]By design, accuracy in the orientation discrimination task was very high (every observer had an overall performance >95%); thus, we analyzed appearance judgments for all trials.

[2]Note that as for the seldom trials in which observers did not maintain fixation, regardless of the effect of saccades on apparent flicker rate (suppression or blurred vision), it should affect test and standard in a similar way and thus not affect their comparison. Moreover, given that perceived flicker rate is overestimated at periphery compared to fovea (Yo & Wilson, 1993), had observers foveated the cued location, we would have expected the effect to be opposite to the one reported here.

[3]Data from one observer for the standard cued condition was excluded from the average and from the statistical analysis because the estimated PSE (20.78 Hz) exceeded the range of temporal frequencies that was used in the experiment.

References

Baldassi, S., Burr, D., Carrasco, M., Eckstein, M., & Verghese, P. (2004). Visual attention (editorial). *Vision Research, 44,* 1189–1191. [PubMed]

Bowker, D. O. (1982). Perceived flicker rate of suprathreshold stimuli: Influences of spatial-frequency content and modulation amplitude. *Journal of the Optical Society of America, 72,* 1652–1659. [PubMed]

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

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

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

Carrasco, M., Giordano, A. M., & McElree, B. (2006). Attention speeds processing across eccentricity: Feature and conjunction searches. *Vision Research, 46,* 2028–2040. [PubMed]

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

Carrasco, M., Loula, F., & Ho, Y.-X. (in press). How attention enhances spatial resolution: Evidence from selective adaptation to spatial frequency. *Perception & Psychophysics.*

Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences of the United States of America, 98,* 5363–5367. [PubMed] [Article]

Carrasco, M., McElree, B., Denisova, K., & Giordano, A. M. (2003). Speed of visual processing increases with eccentricity. *Nature Neuroscience, 6,* 669–670. [PubMed]

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. [PubMed]

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*(6), 467–479, http://journalofvision.org/2/6/4/, doi:10.1167/2.6.4. [PubMed] [Article]

Cheal, M., & Lyon, D. R. (1991). Central and peripheral precuing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology A, Human Experimental Psychology, 43,* 859–880. [PubMed]

Eriksen, C. W. W., & Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics, 12,* 201–204.

Fukuda, T. (1977). Subjective frequency in flicker perception. *Perceptual and Motor Skills, 45,* 203–210. [PubMed]

Fuller, S., & Carrasco, M. (in press). Covert attention and color perception: Performance and appearance of saturation and hue. *Vision Research.*

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

Golla, H., Ignashchenkova, A., Haarmeier, T., & Thier, P. (2004). Improvement of visual acuity by spatial cueing: A comparative study in human and non-human primates. *Vision Research, 44,* 1589–1600. [PubMed]

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

Hartmann, E., Lachenmayr, B., & Brettel, H. (1979). The peripheral critical flicker frequency. *Vision Research, 19,* 1019–1023. [PubMed]

Hein, E., Rolke, B., & Ulrich, R. (2006). Visual attention and temporal discrimination: Differential effects of automatic and voluntary cueing. *Visual Cognition, 13,* 20–50.

Hess, R. F., & Fredericksen, R. E. (2002). Temporal detection in human vision: Dependence on eccentricity. *Ophthalmic & Physiological Optics, 22,* 92–102. [PubMed]

Hess, R. F., & Snowden, R. J. (1992). Temporal properties of human visual filters: Number, shapes and spatial covariation. *Vision Research, 32,* 47–59. [PubMed]

Itti, L., Rees, G., & Tsotsos, J. K. (Eds.). (2005). *Neurobiology of attention*. Burlington, MA: Elsevier/Academic Press.

James, W. (1890/1950). *The principles of psychology*. New York: Henry Holt.

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: Lawrence Erlbaum Associates.

Jonides, J., & Mack, R. (1984). On the cost and benefit of cost and benefit. *Psychological Bulletin, 96,* 29–44.

Kinchla, R. A. (1992). Attention. *Annual Review of Psychology, 43,* 711–742. [PubMed]

Lehky, S. R. (1985). Temporal properties of visual channels measured by masking. *Journal of the Optical Society of America A, Optics and Image Science, 2,* 1260–1272. [PubMed]

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

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

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

Mackeben, M., & Nakayama, K. (1993). Express attentional shifts. *Vision Research, 33,* 85–90. [PubMed]

Mandler, M. B. (1984). Temporal frequency discrimination above threshold. *Vision Research, 24,* 1873–1880. [PubMed]

Mandler, M. B., & Bowker, D. O. (1980). Shifts in apparent flicker rate following flicker adaptation [Abstract]. *Investigative Ophthalmology & Visual Science, 19,* 45.

Mandler, M. B., & Makous, W. (1984). A three channel model of temporal frequency perception. *Vision Research, 24,* 1881–1887. [PubMed]

Marks, L. E. (1970). Apparent depth of modulation as a function of frequency and amplitude of temporal modulations of luminance. *Journal of the Optical Society of America, 60,* 970–977. [PubMed]

Müller, 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. [PubMed]

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

Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

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

Pelli, D. G. (1981). *Effects of visual noise*. Unpublished doctoral dissertation. England, UK: University of Cambridge.

Pestilli, F., & Carrasco, M. (2005). Attention enhances contrast sensitivity at cued and impairs it at uncued locations. *Vision Research, 45,* 1867–1875. [PubMed]

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25. [PubMed]

Prinzmetal, W., Amiri, H., Allen, K., & Edwards, T. (1998). Phenomenology of attention: Part 1. Color, location, orientation, and spatial frequency. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 261–282.

Robson, J. G. (1966). Spatial and temporal contrast sensitivity functions of the visual system. *Journal of the Optical Society of America, 56,* 1141–1142.

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science, 12,* 205–212. [PubMed]

Snowden, R. J., & Hess, R. F. (1992). Temporal frequency filters in the human peripheral visual field. *Vision Research, 32,* 61–72. [PubMed]

Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in human information processing. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, chap. 2, pp. 1–65). New York: Wiley.

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 539–550. [PubMed]

Stelmach, L. B., Herdman, C. M., & McNeil, K. R. (1994). Attentional modulation of visual processes in motion perception. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 108–121.

Talgar, C. P., & Carrasco, M. (2002). Vertical meridian asymmetry in spatial resolution: Visual and attentional factors. *Psychonomic Bulletin & Review, 9,* 714–722. [PubMed] [Article]

Thompson, P., & Stone, L. S. (1997). Contrast affects flicker and speed perception differently. *Vision Research, 37,* 1255–1260. [PubMed]

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

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

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

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

Tyler, C. W. (1987). Analysis of visual modulation sensitivity: III. Meridional variations in peripheral flicker sensitivity. *Journal of the Optical Society of America A, Optics and Image Science, 4,* 1612–1619. [PubMed]

van der Heijden, A. H. C. (1992). *Selective attention in vision*. London: Routledge.

von Helmholtz, H. L. F. (1910/1925). Handbuch der physiologischen Optik [Helmholtz's treatise on physiological optics]. In J. P. C. Southhall (Ed. and Trans.), *Leipzig: Voss* (Vol. 3, p. 455). Rochester, NY: Optical Society of America.

Watson, A. B. (1986). Temporal sensitivity. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, chap. 6, pp. 1–43). New York: Wiley.

Watson, A. B., & Robson, J. G. (1981). Discrimination at threshold: Labelled detectors in human vision. *Vision Research, 21,* 1115–1122. [PubMed]

Weibull, W. (1951). A statistical distribution function of wide applicability. *Journal of Applied Mechanics, 18,* 292–297.

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

Wundt, W. (1902). *Outlines of psychology* (C. H. Judd, Trans.). Leipzig: W. Engelman.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601–621. [PubMed]

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

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

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

Yeshurun, Y., & Levy, L. (2003). Transient spatial attention degrades temporal resolution. *Psychological Science, 14,* 225–231. [PubMed]

Yo, C., & Wilson, H. R. (1993). Peripheral temporal frequency channels code frequency and speed inaccurately but allow accurate discrimination. *Vision Research, 33,* 33–45. [PubMed]