

Attention speeds processing across eccentricity: Feature and conjunction searches

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Abstract

We investigated whether the effect of covert attention on information accrual varies with eccentricity (4° vs 9°) and the complexity of the visual search task (feature vs conjunction). We used speed–accuracy tradeoff procedures to derive conjoint measures of the speed of information processing and accuracy in each search task. Information processing was slower with more complex conjunction searches than with simpler feature searches, and overall it was faster at peripheral (9°) than parafoveal (4°) locations in both search types. Covert attention increased discriminability and accelerated information accrual at both eccentricities, and the magnitude of this attentional effect was the same for both feature (simple) and conjunction (complex) searches. Interestingly, in contrast to the compensatory effect of covert attention on information processing at iso-eccentric locations (temporal performance fields), covert attention did not eliminate speed differences across eccentricity.

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1. Introduction

The human visual system is continually pressed to deal with conflicting environmental demands: High spatial resolution is necessary to process detailed visual information, as in reading text on a page, but high temporal resolution is required to process rapidly changing aspects of the visual environment, as in detecting an approaching car in the periphery. The visual system appears to have evolved a duplex design to efficiently meet these conflicting demands. Spatial resolution is maximal at the fovea and decreases as a function of eccentricity (DeValois & DeValois, 1988; Hilz & Cavonius, 1974). Support for this notion is found in static visual search and acuity tasks, among others, where performance is found to significantly *decrease* as eccentricity increases (e.g. Carrasco & Frieder, 1997; Golla, Ignashchenkova, Haarmeier, & Thier, 2004; Levi, McGraw, &

Klein, 2000; Yeshurun & Carrasco, 1999). However, the periphery is more responsive to temporal properties of the visual world. This fact is supported by measures of temporal resolution (Hartmann, Lachenmayr, & Brettel, 1979), flicker fusion (Hartmann et al., 1979; McKee & Taylor, 1984), and motion detection (Finlay, 1982; McKee & Nakayama, 1984). In task such as these, which require the processing of rapidly changing stimuli, performance *improves* as eccentricity increases.

This design appears to be largely a consequence of the fact that the main projections from the retina to the cerebral cortex are organized into two parallel pathways (M and P), which are relayed through the magnocellular and parvocellular divisions of the LGN and of striate cortex. In macaque and cats, the speed of conduction and integration time are about 20 ms faster for magno than for parvo cells (Lamme & Roelfsema, 2000; Schmolesky et al., 1998). In addition, the ratio of parvo to magno cells decreases with eccentricity (Azzopardi, Jones, & Cowey, 1999). The spatiotemporal characteristics of these two pathways have

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been shown to have direct consequences on visual processing (e.g., Lennie, 1998).

The current investigation focuses on the speed of information processing at different eccentricities, and how the speed of information accrual may be modulated by attentional demands. Carrasco, McElree, Denisova, and Giordano (2003) hypothesized that the heightened responsiveness of the periphery to temporal properties may be partly due to the speed with which visual information is processed at different eccentricities. Given the similarities between the visual systems of human and nonhuman primates, it is reasonable to assume that differences in ratio of parvo to magno cells at different eccentricities may enable faster processing of visual stimuli in peripheral than in parafoveal regions. To test this hypothesis, Carrasco et al. (2003) used the speed–accuracy tradeoff (SAT) procedure, which provides conjoint measures of discriminability and information accrual (Reed, 1973; see below), to examine the speed of processing in a feature search task. They found that information processing was faster at peripheral (9°) than at parafoveal (4°) eccentricities, providing direct behavioral evidence that the speed of processing varies as a function of eccentricity. One goal of the present study was to investigate whether the effect of eccentricity on speed of processing is affected by the complexity of processing, and for that reason we used feature and conjunction searches, visual tasks that differ in complexity.

As discussed more fully in Section 1.2, in another study, Carrasco, McElree and Giordano (2004) used the SAT procedure to examine the speed of processing at different iso-eccentric locations within the visual field (eight equidistant cardinal and intercardinal locations around fixation). They found that processing speed varied at iso-eccentric locations. However, when transient, exogenous covert attention (hereafter referred to simply as ‘attention’) was directed to the relevant target location, asymmetries in processing speed were virtually eliminated, resulting in uniform processing speeds at all iso-eccentric locations. Our second goal of the current study was to determine whether covert attention modulates or perhaps even eliminates the speed differences at different eccentricities in both simple and complex tasks.

1.1. Visual search and eccentricity

In the current study, we first sought to examine whether eccentricity has the same effect on discriminability and processing dynamics in search tasks of different complexity. Feature search (e.g., searching for a target of one orientation among distractors of another orientation) is often used to examine how the visual system extracts basic features. Reaction time (RT) and accuracy for detecting or discriminating a target are largely unaffected by the number of distractors (set size) in feature search. Conjunction search (searching for a unique combination of two features—e.g., orientation and spatial frequency—among distractors

that share only one of these features) is often used to examine how the system combines features into perceptual wholes. In this case, RT increases and accuracy decreases with the number of distractors.

Early approaches argued that these different search patterns reflect ‘parallel’ pre-attentive and ‘serial’ attentional mechanisms, respectively (e.g. Treisman & Gelade, 1980; Treisman, Vieira, & Hayes, 1992; Wolfe, 1994; Wolfe & Cave, 1990). However, numerous studies have challenged this dichotomy and have suggested that a parallel processing mechanism underlies both feature and conjunction searches (e.g. Cameron, Tai, Eckstein, & Carrasco, 2004; Carrasco & McElree, 2001; Carrasco & Yeshurun, 1998; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Kinchla, 1992; McElree & Carrasco, 1999; Palmer, 1994; Verghese & Nakayama, 1994). Nevertheless, conjunction searches are viewed as more complex than feature searches, as they require combining information from two separate feature dimensions rather than searching for a target that differs from all distractors by only one feature. As the two tasks presumably require different degrees of attentional involvement, it is of interest to determine whether the effects of eccentricity are comparable.

Our main focus in the present study is on temporal dynamics. Consistent with a study by McElree and Carrasco (1999), which documented differences in the temporal dynamics of feature and conjunction searches, we predicted that the speed of processing would be slower in conjunction searches than in feature searches as a result of the inherent complexity of the former. Consistent with Carrasco et al.’s (2003) study, which showed that information accrual is faster at farther eccentricities, we also predicted that processing speed will be slower at parafoveal (4°) than peripheral (9°) locations in both simple (feature) and complex (conjunction) tasks. We manipulated stimulus parameters so as to equate discriminability across task and eccentricity.

1.2. Covert attention and visual field

The second goal of this study was to determine whether attention speeds information processing across the visual field uniformly in both simple and complex tasks. Attention allows us to grant priority in processing for visual information at a given location without eye movements. It can be voluntarily allocated to a location according to an observer’s goals (‘sustained attention’), or involuntarily allocated, in a reflexive manner, to a cue that appears suddenly in the visual field (‘transient attention’). Attention improves discriminability in a variety of early visual tasks, such as contrast sensitivity (Carrasco, Penpeci-Talgar, & Eckstein, 2000; Ling & Carrasco, 2006; Lu & Doshier, 1998; Solomon, Lavie, & Morgan, 1997); acuity (Carrasco, Williams, & Yeshurun, 2002; Golla et al., 2004); texture segmentation (Yeshurun & Carrasco, 1998, 2000) and visual search (Carrasco & McElree, 2001; Carrasco & Yeshurun, 1998; Nakayama & Mackeben, 1989). Crucially, we

have shown that attention not only improves discriminability but also accelerates information accrual at the cued location. By improving discriminability, attention enables us to extract relevant information in a noisy environment; by accelerating processing, it enables us to extract information efficiently in a dynamic environment, before potentially interfering stimuli occur (Carrasco & McElree, 2001; Carrasco, Giordano, & McElree, 2004; Carrasco, Ling, & Read, 2004).

Attention is known to have both uniform and compensatory effects on performance depending on the dimension (space or time) and location in the visual field being examined. Carrasco, Talgar, and Cameron (2001) have explored the visual factors that underlie *spatial* performance fields. Discriminability is highest along the horizontal meridian (East and West locations) of the visual field, followed by intercardinal locations (Northeast, Northwest, Southeast and Southwest), and then the vertical meridian (North and South locations). Within the vertical meridian, discriminability was worse at the North compared the South location. These effects, known as the horizontal vertical anisotropy (HVA) and the vertical meridian asymmetry (VMA), are accentuated with increasing spatial frequency or eccentricity. Given that attention increased discriminability at each location to the same degree, resulting in the same pattern of performance, Carrasco et al. (2001) concluded that visual constraints are responsible for spatial performance fields. We might likewise expect that attention would increase discriminability uniformly across the visual field in search tasks. Alternatively, given that attention enhances spatial resolution to a larger degree at peripheral regions, where resolution is worse (Carrasco & Yeshurun, 1998; Carrasco et al., 2002), we might expect attention to have a compensatory effect on discriminability by enhancing sensitivity more at locations where contrast sensitivity is poorer.

Carrasco and Giordano et al. (2004) have documented the existence of *temporal* performance fields. They found that the pattern of information accrual for iso-eccentric locations mimics the pattern of spatial performance: Processing is fastest along the horizontal meridian (East and West locations), followed by the intercardinal locations (Northeast, Northwest, Southeast, and Southwest), with the vertical meridian being slowest (North and South locations). Again, within the vertical meridian, processing is slower at the North compared the South location. However, unlike the uniform effect attention had on the spatial performance fields, attention had a compensatory effect on temporal performance fields: It sped processing most along the vertical meridian (with a higher boost at the North compared to the South locations), followed by the intercardinal locations (Northeast, Northwest, Southeast, and Southwest), and the smallest effect was found along the horizontal meridian (East and West). Attention sped processing most at locations where processing was slowest, thereby virtually eliminating the speed differences found at iso-eccentric locations of the

visual field. Attention may have a similar compensatory effect on temporal processing in search tasks, speeding processing more at slower central locations. Alternatively, following the idea that peripheral locations generally receive less attention than parafoveal locations, it is possible that attention could exaggerate the speed differences because information is already processed faster at peripheral locations.

In sum, existing literature supports the different predictions of attention on discriminability and temporal dynamics of visual processing—it may have uniform, compensatory, or exaggerated effects.

1.3. SAT procedure: Measuring discriminability and temporal dynamics

How should the speed of visual processing be measured? Studies showing that presenting information at a peripheral location (Breitmeyer, 1984) or precueing target location (Jonides, 1981; Posner, 1980; Yeshurun & Carrasco, 1999) reduces the time to respond (RT) to a stimulus do not speak directly to the issue of whether information processing is faster at either more peripheral locations or precued target locations. Response time differences can be due to changes in decision criteria or discriminability (McElree & Doshier, 1989; Reed, 1973; Wickelgren, 1977). Decision criteria can vary across conditions, leading to speed–accuracy tradeoffs. Even when decision criteria remain constant, differences in discriminability alone can lead to differences in response time. Models of response time typically assume a response is executed when information accumulation exceeds a criterion value (McElree & Doshier, 1989). Typically, a response threshold will be reached at an earlier point in time if a stimulus is more discriminable, even when the speed of information accumulation is the same as for a less discriminable stimulus.

A solution to this problem is to employ the response-signal SAT procedure, which controls for tradeoffs and provides conjoint measures of discriminability and information accrual (e.g. Doshier, Han, & Lu, 2004; McElree & Carrasco, 1999; McElree & Doshier, 1989; Reed, 1973; Wickelgren, 1977). This procedure enables the measurement of the speed of information processing in circumstances in which discriminability varies. We have previously used this methodology to assess the speed of information processing across eccentricity (Carrasco et al., 2003) and iso-eccentric locations (Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004), as well as the effect of attention on visual search of feature and conjunctions (Carrasco & McElree, 2001). Here, we used SAT methodology to examine whether eccentricity has the same effect on discriminability and processing dynamics in search tasks of different complexity, i.e., features and conjunctions, as well as to determine whether covert attention speeds information processing across the visual field uniformly.

2. Experiment

Observers performed two tasks, a feature¹ and a conjunction search task, at 4° and 9° eccentricity. The stimuli used in these tasks are Gabor patches (supra-threshold sinusoidal gratings vignettted by a Gaussian envelope) that are well matched to early linear spatial filters in the visual system, and which varied in two basic dimensions, orientation and spatial frequency. Both tasks required a two-alternative forced choice discrimination, in which observers indicated whether a 2 cycle per degree (cpd) Gabor target was tilted 30° to the right or to the left. In the feature search, 3 or 7 distracters, vertical 2-cpd Gabor patches, were used. In the conjunction search, approximately half of these distracters shared the orientation of the target, and half the spatial frequency. We manipulated attention by presenting a peripheral precue (a small circle adjacent to the target location; e.g. Carrasco et al., 2000, 2002; Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004; Jonides, 1981; Nakayama & Mackeben, 1989; Yeshurun & Carrasco, 1998, 2000) on a random half of the trials.

We used the SAT procedure to obtain separate estimates of discriminability and processing time. Fig. 1, in which discrimination performance is plotted as a function of processing time, displays hypothetical SAT functions. Fig. 1A illustrates a case where discriminability alone varies with an experimental variable (e.g., eccentricity or attention). Enhanced discriminability yields stronger evidence, and thereby engenders higher asymptotic performance. Fig. 1B illustrates conditions that differ in the speed of processing, with Condition A being faster. Underlying differences in processing speed will engender differences in the intercept of the SAT function, the rate at which the function approaches asymptote, or both parameters (as illustrated in Fig. 1B). The intercept ($d' = 0$) measures the minimal time needed for above-chance discrimination. The rate of rise of the function indexes either the rate of information accrual directly, if the underlying process is continuous, or the distribution of finishing times, if the underlying processing is discrete (Doshier, 1979; Meyer, Irwin, Osman, & Kounois, 1988; Ratcliff, 1988). A difference in either rate or intercept will result in disproportional SAT dynamics, in that the functions will reach a given proportion of their respective asymptotes at different times. The lines that intersect the ordinate and abscissa in Fig. 1 show the time when the functions reach the $1 - 1/e$ (63%) point. In Fig. 1A, where the processing speed is identical, the functions reach this point at the same time as indicated by the vertical line. In Fig. 1B, where the functions are associated with a common asymptote but different rates and intercepts, the $1 - 1/e$ point is reached at different

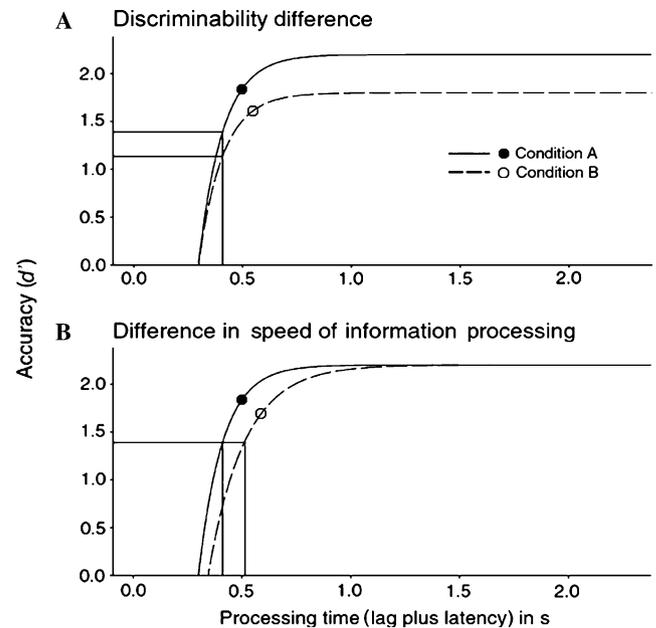


Fig. 1. Hypothetical SAT functions. Illustrative SAT functions, plotted in d' units ($\sqrt{2}$ of the standard normal deviate of the probability of correctly judging the target's orientation) vs processing time (time of the response cue plus observer's average latency to respond). (A) Expected pattern if an experimental factor increases target discriminability only. The functions differ in asymptotic accuracy, but are associated with the same intercept (point when accuracy departs from chance) and proportional rate of information accrual. (B) One expected pattern if the experimental factor alters the speed of information accrual (intercept and rate) only. The functions display disproportional dynamics; they reach a given proportion of their asymptotes at different times. Circles show hypothetical results from a typical RT task plotted in SAT coordinates (abscissa = mean RT; ordinate = accuracy), illustrating that RT differences can reflect differences in discriminability (A) or information accrual (B). The position of the RT points on the corresponding SAT functions are determined by the decision criteria that an observer uses to balance speed and accuracy.

times. The circles show the corresponding RT points in SAT coordinates, illustrating that RT differences can arise from differences in either discriminability (Fig. 1A) or dynamics (Fig. 1B).

3. Methods

3.1. Observers

Three NYU students participated in this experiment. They were naïve as to the purposes of the study, and all had normal or corrected-to-normal vision.

3.2. Apparatus

The stimuli were created using Matlab and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Observers viewed the stimuli on a gamma-corrected monitor (Pelli & Zhang, 1991). A video attenuator was used to drive just the green gun of a 21" IBM P260 monitor (1024 × 768; 120 Hz), providing a larger possible set of distinct luminance levels (~12.6 bits). Background luminance was set to the middle of the monitor's range (16 cd/m²).

¹ The data for the feature search in the neutral condition (Fig. 3A) have been previously reported (in Fig. 2A of Carrasco et al., 2003; Brief Communication in *Nature Neuroscience*).

3.3. Stimuli and design

All Gabor patches subtended 2° of visual angle (full width at $1/e$), on the basis of a fixed 114 cm viewing distance. A small fixation dot ($.2 \times .2^\circ$ of visual angle) was presented at the center of the screen throughout the experiment. The stimuli were randomly presented at 8 equidistant locations (at the cardinal and intercardinal locations) from a central fixation point on an invisible polar grid at 4° or 9° eccentricity.

In the feature search, observers responded to a unique visual feature (30° tilt) presented in isolation or with 3 or 7 distracters of a different orientation (all distracters were vertical 2-cpd Gabor patches). In the conjunction search, observers responded to a unique conjunction of two features—spatial frequency and orientation—presented in isolation or with 3 or 7 distracters (2 or 4 distracters shared the target's orientation, and 1 or 3 shared its spatial frequency).

3.4. Procedure

We manipulated attention by presenting a peripheral precue, which appeared for 67 ms (small circle, $.3 \times .3^\circ$ of visual angle, appearing 2° from the center of target), on a random half of the trials. This precue indicated to the observer the display onset and target location but did not signal the target orientation. A neutral precue (a small circle in the middle of the display) was presented on the remaining trials indicating the display onset and that the target and distracters had equal probability of appearing at any of the 8 locations. As illustrated in Fig. 2, the Gabor patches, with 0, 3 or 7 distracters, appeared briefly after an inter-stimulus interval (ISI) of 53 ms. The interval between cue and target onsets maximized the attentional benefit, which occurs at about 80–120 ms (Carrasco & Ling et al., 2004; Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Given that 200–250 ms are needed for a saccade to occur (Mayfrank, Kimmig, & Fischer, 1987), the interval between the cue onset and the stimulus offset was brief enough to prevent goal (or target) directed eye movements. A small fixation dot was always present at the center of the screen. Both feature and conjunction search tasks required a two-alternative forced choice discrimination: Observers were asked to respond whether a 2-cpd Gabor target was tilted to the right or to the left.

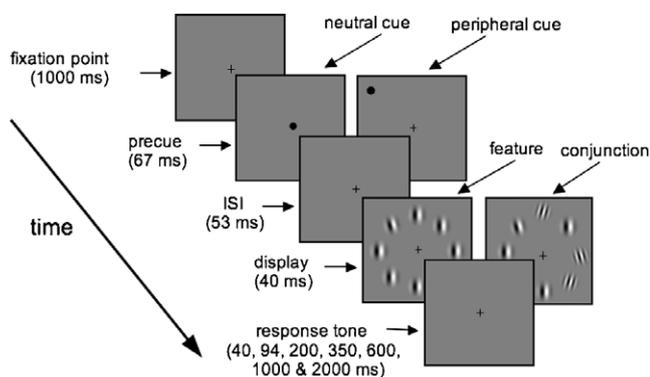


Fig. 2. Sequence of events in a single trial. The stimuli were randomly presented at 8 equidistant locations from a central fixation point on an invisible polar grid at either 4° or 9° eccentricity. In these examples, the target—low spatial frequency, tilted to the left Gabor—is at the NW location. In both task types, the targets were 2-cpd patches tilted 30° to the right or the left. In the feature task the distracters were vertical 2 cpd patches; in the conjunction task, distracters shared either the orientation or the spatial frequency of the target [the 2-cpd distracters were vertical patches and the half the 8-cpd distracters tilted to the right and half to the left]. To implement the SAT procedure, a response tone was presented after the display at varying time lags ranging from 40 to 2000 ms. Feedback was provided after each trial and block.

To measure discriminability and information accrual conjointly in neutral and cued conditions (Carrasco et al., 2003; Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004; Carrasco & McElree, 2001), a tone sounded at one of seven randomly chosen times ranging from 40 to 2000 ms after the display onset. Observers were required to respond within 350 ms after the tone. Feedback on the latency to respond to the tone was given after each trial and block. The range of response times enabled us to sample the full time-course of processing, from early times when discrimination was at or near the chance level to late times when it had reached its maximal, asymptotic level.

The search type (feature vs conjunction) and stimulus eccentricity (4° , parafoveal vs 9° , peripheral) were counterbalanced across observers. Two of the 3 observers performed both tasks at 4° eccentricity first. All variables—cue type: neutral vs peripheral; set size: 1, 4 or 8; and response tone: 40, 94, 200, 350, 600, 1000 and 2000 ms—were randomly presented within each block of feature and conjunction searches. All observers completed 1 practice session to accustom themselves to the task, particularly to the deadline procedure. Each observer performed a total of 26,880 experimental trials over twenty-eight 90-min sessions (40 trials per data point: 2 type searches \times 3 set sizes \times 2 cue conditions \times 8 locations \times 7 lags). Prior to testing, stimulus contrast was adjusted for each observer so that the average performance across all response lags was at 80–85% correct level. The contrasts for the 2-cpd suprathreshold stimuli ranged (across observers) from 8 to 12% for 4° and 9° eccentricity, and the contrast for the 8-cpd suprathreshold stimuli ranged from 70 to 80% for 4° and 9° eccentricity. Stimulus contrast was constant for each observer at each frequency for both eccentricities, given that contrast sensitivity is virtually the same for 4° and 9° eccentricity (Banks, Sekuler, & Anderson, 1991); pilot data confirmed this.

4. Results

The time course data for each of the three observers and for the average over observers were fit with an exponential approach to a limit:

$$d'(t) = \lambda(1 - e^{-\beta(t-\delta)}), \quad \text{for } t > \delta, \text{ else } 0. \quad (1)$$

The parameters of Eq. (1) provide a quantitative summary of the shape of the SAT function (Reed, 1973; Wickelgren, 1977), λ is the asymptotic parameter reflecting discriminability at maximal processing time; δ is the intercept parameter reflecting the discrete point in time when discriminability departs from chance ($d' = 0$); β is the rate parameter indexing the speed with which discriminability grows from chance to asymptote. A hierarchical model-testing scheme was used to determine how the experimental factors affected the three parameters of Eq. (1). Parameter estimates for the best fitting models to the average data for all conditions (two search types, 3 set sizes for 2 eccentricities under 2 cueing conditions) are shown in Tables 1 and 2 and Figs. 3 and 4, and the differences among the various conditions are described below.

4.1. Exponential fits

Eq. (1) was used for a quantitative summary of the shape of the SAT function (McElree & Carrasco, 1999; McElree & Doshier, 1989; Reed, 1973; Wickelgren, 1977). We used a hierarchical model-testing scheme to determine how the experimental factors—eccentricity, cueing type and set size—affected the shape of the SAT functions in both feature and conjunction searches. The three parameters

Table 1
Exponential parameter estimates (est.) and standard deviations (SD) for the best fitting models presented in Figs. 3 and 4

	Neutral 4°		Neutral 9°		Peripheral 4°		Peripheral 9°	
	Est.	SD	Est.	SD	Est.	SD	Est.	SD
<i>Feature search</i>								
Discriminability (λ in d' units)								
Set size 1	1.62	0.05	1.93	0.05	1.87	0.06	1.95	0.06
Set size 4	1.46	0.06	1.55	0.05	2.04	0.06	1.98	0.06
Set size 8	1.36	0.05	1.65	0.06	1.92	0.06	1.86	0.06
Processing speed (in ms)								
Rate ($1/\beta$ for all set sizes)	99	8	99	11	85	8	85	14
Intercept (δ for all set sizes)	298	6	211	5	259	5	182	4
<i>Conjunction search</i>								
Discriminability (λ in d' units)								
Set size 1	1.71	0.05	1.81	0.05	2.12	0.06	1.95	0.06
Set size 4	1.38	0.06	1.67	0.06	1.89	0.06	1.81	0.06
Set size 8	1.22	0.05	1.56	0.06	1.81	0.06	1.95	0.06
Processing speed (in ms)								
Rate ($1/\beta$)								
Set size 1	83	5	83	11	72	8	72	13
Set size 4	157	14	157	10	67	7	67	12
Set size 8	192	14	192	12	88	6	88	15
Intercept (δ for all set sizes)	305	12	205	6	297	17	191	5

Table 2
Composite processing time ($\delta + 1/\beta$) in ms, from exponential fits

	4° eccentricity	9° eccentricity	Speed difference (eccentricity)
<i>Feature search (for all set sizes)</i>			
Neutral	397	310	87
Peripheral	343	267	76
Speed difference (cue)	54	43	—
<i>Conjunction search</i>			
Neutral			
Set size 1	388	288	100
Set size 4	462	362	100
Set size 8	497	397	100
Peripheral			
Set size 1	369	263	106
Set size 4	364	258	106
Set size 8	385	279	106
Speed difference (cue)			
Set size 1	19	25	—
Set size 4	98	104	—
Set size 8	112	118	—

of the exponential equation were fit to each observer's data and the average data. These models ranged from a null model in which the functions of interest were fit with a single asymptote (λ), rate (β), and intercept (δ), to a fully saturated model in which each function was fit with a unique set of parameters. The quality of fit was determined by three criteria: (1) The value of an adjusted R^2 statistic (Reed, 1973) where the proportion of variance accounted for by a model was adjusted by the number of free parameters. (2) The consistency of parameter estimates across observers. (3) An evaluation of whether any fit left system-

atic residuals that could be accounted for by additional parameters.

To calculate error on each of the parameter estimates, a bootstrapping procedure was performed for each of the SAT functions (Wagenmakers, Ratcliff, Gomez, & Iverson, 2004). One thousand simulated SAT data points were generated based on the original estimates that were derived from each of the observer's data set. Each set of 1000 data points was then fit to an exponential function and new parameter estimates were derived from this simulated data set. This procedure was repeated 100 times (1000 simulated data points \times 100 times) for each SAT curve. Standard deviations were then calculated on each of the 100 estimates for each parameter (asymptote, rate and intercept). Table 1 also gives the set of parameter estimates and the standard deviations for each SAT function.

The results for the feature search have been previously summarized in a brief report (Carrasco et al., 2003). We report this analysis here so that we can directly compare the pattern to one observed in the conjunction search in the neutral condition, and so that we can address the effects of attention in both search tasks. First, we report that speed of information processing was slower with more complex conjunction searches than with simpler feature searches. Second, we demonstrate that attention speeds up processing homogeneously across eccentricity and search type. Below we document these effects, focusing first on the neutral cue condition.

4.2. Features

Fig. 3A displays the average time-course functions for feature searches in the neutral condition, when the target

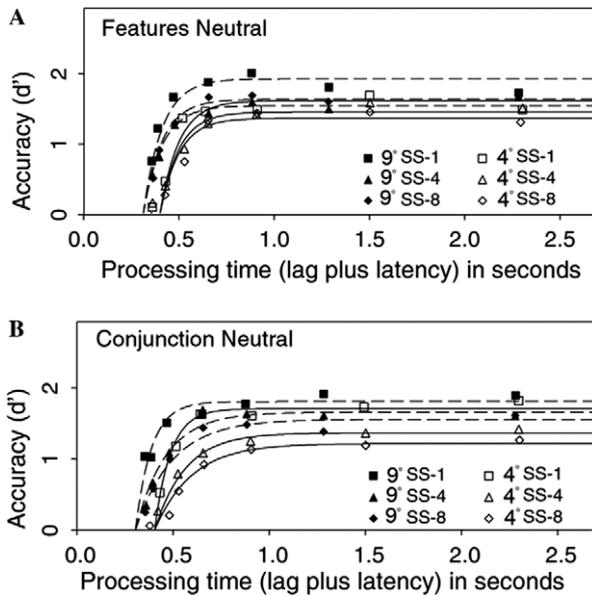


Fig. 3. Results. Average discrimination accuracy (in d' units) as a function of processing time in feature (A) and conjunction (B) searches under neutral cueing conditions. Smooth functions show the best-fitting exponential model (Eq. (1)) for 4° (solid lines) and 9° (dashed lines) conditions, based on fits of nested models that systematically varied the three parameters of Eq. (1). Table 1 shows average parameter values for both sets of fits. The data reported in (A) had been reported in Carrasco et al. (2003; Fig. 2A). They are presented here for purposes of comparison.

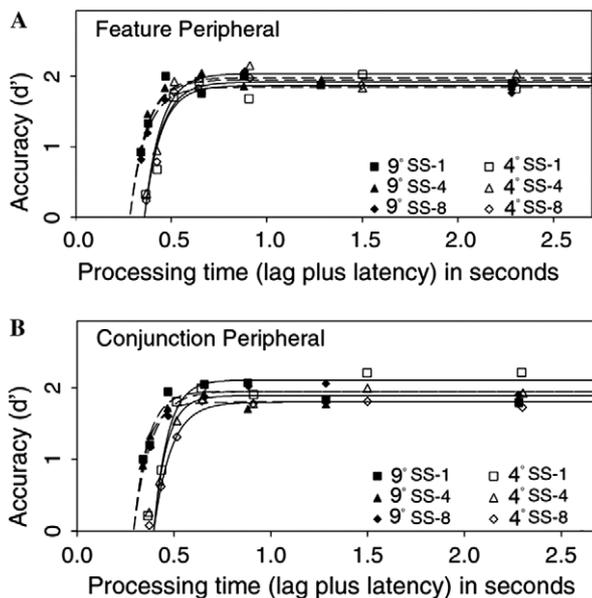


Fig. 4. Results. Average discrimination accuracy (in d' units) as a function of processing time in feature (A) and conjunction (B) searches under peripheral cueing conditions. Smooth functions show the best-fitting exponential model (Eq. (1)) for 4° (solid lines) and 9° (dashed lines) eccentricity conditions, based on fits of nested models that systematically varied the three parameters of Eq. (1). Table 1 shows average parameter values.

location was not cued. Model fits indicated that set size affected discriminability but not processing speed (β or δ parameter) at each eccentricity. The best-fitting model for the feature searches allocated a separate asymptotic param-

eter (λ) to each of the 6 conditions, a common rate (β) parameter, and one intercept (δ) parameter to 4° eccentricity conditions and another to 9° eccentricity conditions (adjusted $R^2 = .951$ for the average data, ranging from .857 to .891 across observers). Table 1 shows average parameter values for this fit.

These findings replicated previous results (Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004; Carrasco & McElree, 2001; McElree & Carrasco, 1999). Asymptotic discriminability (λ) decreased as set size increased from 1 to 8, by $.26d'$ units (ranging from .15 to .37 for individual observers) at 4° eccentricity and by $.28d'$ units (.18 to .59 across observers) at 9° eccentricity. The observed reduction in asymptotic discriminability with larger set sizes is consistent with several “confusability” accounts of visual search (Cameron et al., 2004; Eckstein et al., 2000; Kinchla, 1992; Palmer, 1994; Shaw, 1984) in which the signal-to-noise ratio decreases with number of distracters, leading to an increased likelihood of a decision error.

Although stimulus contrast was kept constant at both eccentricities in an attempt to match overall discriminability (Banks et al., 1991), asymptotic accuracy was nonetheless slightly higher at 4° than 9° eccentricity, by an average of $.23d'$ units (.1 to .39 across observers). Notably, however, processing speed was much faster at 9° than 4° eccentricity. The speed differences were best expressed as an 87 ms (113, 67, and 87 ms for individual observers) advantage in intercept for 9° eccentricity, reflecting the fact that the minimum processing time needed for above chance performance was lower for stimuli at 9° than 4° eccentricity. Model fits that did not allocate separate intercept parameters to the different eccentricities produced a lower adjusted R^2 than a model that varied intercept (.836 vs .952).

4.3. Conjunctions

Fig. 3B displays the average time-course functions for conjunction searches in the neutral condition. Model fits indicated that set size affected both discriminability and processing speed at each eccentricity. The best-fitting model for conjunction searches allocated a separate asymptotic parameter (λ) to each of the 6 conditions, a separate rate (β) parameter to each of the 3 set sizes, and one intercept (δ) parameter to 4° eccentricity conditions and another to 9° eccentricity conditions (adjusted $R^2 = .958$ for the average data, ranging from .808 to .953 across observers). Table 1 shows average parameter values for this fit. As with feature searches, asymptotic discriminability (λ) decreased as set size increased from 1 to 8, by $.49d'$ units (.33 to .65 across observers) at 4° eccentricity and by $.25d'$ units (.11 to .45 across observers) at the 9° eccentricity. In contrast to feature searches, however, processing speed slowed as the number of distracters increased. At both eccentricities, this speed difference was best described as a slowing of the rate (β) parameter, which increases by 110 ms (in $1/\beta$ in units; 49–126 across observers) as number of distracters increased from 0 to 7. The magnitude of the set-size effect

on asymptote and rate were consistent with previous findings. As in the case of feature search, asymptotic differences follow from “confusability” accounts of visual search (Cameron et al., 2004; Eckstein et al., 2000; Kinchla, 1992; Palmer, 1994; Shaw, 1984). Rate differences as a function of set size implicate some type of capacity-limited processing. Model fits presented in McElree and Carrasco (1999) suggest that these differences are best viewed as arising from a capacity-limited parallel model of visual search (see also, Carrasco & McElree, 2001).

Accuracy was again slightly higher at 9° than 4° eccentricity by an average of .24 d' units (.01 to .63 across observers). As with feature searches, processing speed was substantially faster at 9° than 4° eccentricity, and model fits that did not allocate separate intercept parameters to the different eccentricities produced a lower adjusted R^2 than a model that varied intercept (.838 vs .958). The estimated difference in intercept was 100 ms (110, 67, and 113 ms for individual observers), which was quite comparable to the differences found in feature searches.

4.4. Precueing target location

The average time-course functions when the target location was precued are displayed in Fig. 4A for feature and Fig. 4B for conjunction searches. Previous research has shown that precueing the target location improves discriminability and speeds information accrual in both feature and conjunction searches, and that it attenuates the effect of set-size on discriminability in both search tasks and the effect of set size on the speed of processing in conjunction searches (Carrasco & McElree, 2001). The parameter estimates reported in Table 1 show a similar effect. The novel finding is that precueing speeded processing to a similar degree across eccentricity. Thus, the peripheral advantage persisted even when attention was allocated to the relevant location. In what follows, we document this pattern more fully.

The best-fitting model for the feature searches allocated a separate asymptotic parameter (λ) to each of the 6 conditions, a common rate (β) parameter, and one intercept (δ) parameter to 4° eccentricity conditions and another to 9° eccentricity conditions (adjusted $R^2 = .921$ for the average data, ranging from .714 to .900 across observers). The best-fitting model for conjunction searches allocated a separate asymptotic parameter (λ) to each of the 6 conditions, a separate rate (β) parameter to each of the 3 set sizes, and one intercept (δ) parameter to 4° eccentricity conditions and another to 9° eccentricity conditions (adjusted $R^2 = .952$ for the average data, ranging from .840 to .932 across observers).

4.4.1. Discriminability

Precueing the target location increased asymptotic accuracy in the feature task by .46 d' units (.37 to .63 across observers) at the 4° and by .22 d' units (.17 to .23 across observers) at 9° eccentricity. Likewise, for conjunction searches, precueing the target location increased asymptotic

accuracy by .51 d' units (.34 to .66 across observers) at 4° and by .22 d' units (.21 to .39 across observers) at 9° eccentricity. Precueing the target location practically eliminated the set size differences in both tasks (Fig. 4 and Table 1).

4.4.2. Processing speed

As the neutral and precued conditions were associated with different rates and intercepts (Table 1), processing speed is best contrasted with a composite measure, $\delta + \beta^{-1}$, which gives an average processing time in millisecond units (Table 2). This measure guards against potential parameter tradeoffs, where a difference in one temporal parameter may be offset by a difference in the other temporal parameter (e.g., a faster rate but a later intercept), and it also enables cross-condition comparisons when rate and intercepts are not constrained to be equal across the conditions of interest. The composite speed measure indicated that precueing the target location sped processing in the feature task by 53 ms (24 to 76 ms across observers) at 4° and by 43 ms (25 to 63 ms across observers) at 9° eccentricity. Likewise, for conjunction searches, precueing the target location sped processing by 76 ms (60–93 ms across observers) at the 4° and by 82 ms (57–104 ms across observers) at the 9° eccentricity (average across the set size differences in β). In conjunction searches, precueing the target location practically eliminated the effect of set size on the rate of processing, reducing the range from 158 to 17 ms (Fig. 4 and Table 1). This finding replicated the findings of Carrasco and McElree (2001).

The novel result is that precueing the target location did not alter the intercept differences between 4° and 9° eccentricities that were found in the neutral-cueing condition. Indeed, the differences were remarkably similar: In the peripheral-cueing condition, the intercept for the 9° eccentricity condition was 77 ms (39, 85 and 101 for individual observers) earlier than for the 4° eccentricity condition in feature searches and 106 ms (72, 104 and 136 for individual observers) earlier in conjunction searches; in the neutral-cueing condition, the corresponding average values were 87 and 100 ms. Again, model fits that did not allocate separate intercept parameters to the different eccentricities were extremely poor (adjusted $R^2 = .690$ vs .921 and .675 vs .952 for peripherally cued feature and conjunction searches, respectively).²

² For comparison purposes, we provide below the adjusted R^2 values from a fit of a fully saturated model to the four experimental conditions. In parentheses we include the value of the best fit for each condition (determined by a combination of the highest adjusted R^2 statistic, consistency of estimates across observers and whether any residual could be accounted for with additional parameters), which are reported in the text. Feature neutral = .957 (.951); feature peripheral = .911 (.921); conjunction neutral = .972 (.958); conjunction peripheral = .948 (.952). The fully saturated model provides a marginal benefit for the two neutral conditions. However, the best fit provides a comparable marginal benefit for the peripheral conditions. Given the negligible difference between the fits, and that the unconstrained fully saturated model has many more degrees of freedom, we have reported in detail the best fit and base our interpretation of results in such fits.

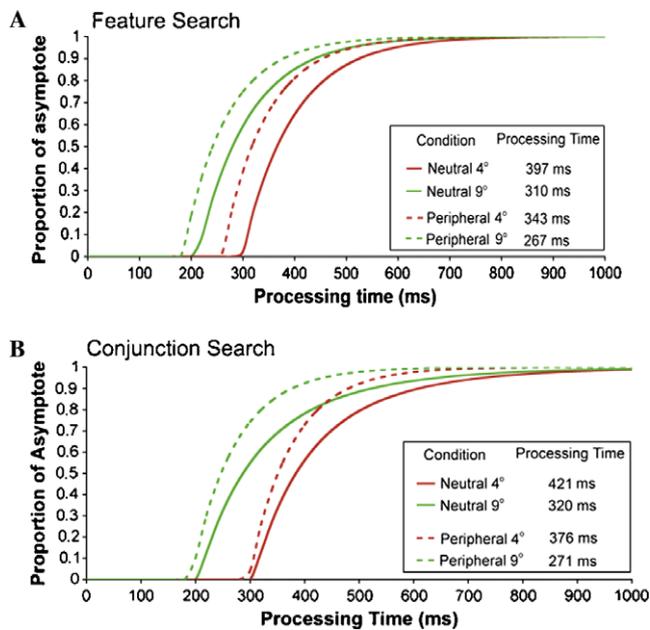


Fig. 5. Speed of information accrual. Relative differences in processing speed for feature (A) and conjunction (B) searches at 4° and 9° (average over set sizes). Differences in processing speed are illustrated by plotting the time at which each condition reaches a given proportion of its asymptote, using the best fitting exponential parameters (Tables 1 & 2) based on fits of nested models that systematically varied the three parameters of Eq. (1). The data reported in (A) corresponding to the neutral functions had been reported in Carrasco et al. (2003; Fig. 2B). They are presented here for purposes of comparison.

The relative differences in processing speed at 4° and 9° are graphically illustrated in Fig. 5 for feature (A) and conjunction (B) searches. We summarized differences in processing speed by plotting the time at which each condition reaches a given proportion of its asymptote, using the best fitting exponential parameters (Tables 1 and 2). Peripheral cueing sped processing for both search types and across eccentricity to a similar extent, thus preserving the relative ordering and differences among conditions.

5. Discussion

This study provides direct behavioral evidence that eccentricity has similar effects on the speed of information accrual for feature and conjunction searches, despite the fact that they differ in complexity. The evidence also demonstrates that attention affects speed of information processing to a similar degree across eccentricity for different types of search.

How attention modulates the speed of processing remains an open issue. Significant progress has been made in understanding how attention affects discriminability, which has led to the development of psychophysical models and the elicitation of possible neurophysiological bases of attention (e.g. Baldassi, Burr, Carrasco, Eckstein, & Verghese, 2004; Carrasco, 2005; Lu & Doshier, 2005; Reynolds, 2005; Martinez-Trujillo & Treue, 2005). For example, the

most prominent psychophysical models explaining how attention affects contrast sensitivity include either a mechanism for signal enhancement (the representation of the signal is enhanced) or a mechanism for external noise reduction (the representation of the external noise is suppressed). Research suggests that attentional effects might reflect a combination of both of these mechanisms (e.g. Carrasco et al., 2000, 2002; Cameron, Tai, & Carrasco, 2002). Single-unit recording studies in the monkey have provided detailed, quantitative descriptions of how attention alters visual cortical neuron responses. A number of studies show that attentional facilitation and attentional selection may come about by increasing contrast sensitivity in extrastriate cortex in a way comparable to increasing stimulus contrast (for reviews, see Carrasco, *in press*; Reynolds & Chelazzi, 2004). Unfortunately, much less is known about the psychophysical and neurophysiological mechanisms that enable attention to modulate the temporal dynamics of information processing, as reported here and in previous studies (Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004; Carrasco & McElree, 2001). The results reported here may provide important constraints for future models for the effects of attention on temporal dynamics.

5.1. Visual search and the number of distractors

Consistent with other studies (Carrasco & McElree, 2001; McElree & Carrasco, 1999), we found that set size affected discriminability in both search tasks, and it also slowed the rate of information processing in the more complex conjunction search task. That set size affects the speed of information accrual in conjunction searches but not in feature searches appears to implicate a type of capacity limitation. Although one might assume that this pattern provides support for a serial search model, McElree and Carrasco (1999) found that explicit serial search models do not adequately fit the observed dynamics differences. Rather, the observed dynamics are more consistent with a limited-capacity parallel search process (see also Carrasco & McElree, 2001). This approach shares much in common with other work in which capacity has been an important construct in explaining visual performance (e.g. Bundesen, 1990; Meyer et al., 1988; Rumelhart, 1970; Shaw & Shaw, 1977; Townsend & Ashby, 1983). For example, we share the assumption that the number of concurrent comparisons determines the overall rate of informational accrual (e.g. Murdock, 1971; Rumelhart, 1970; Shaw & Shaw, 1977; Townsend & Ashby, 1983). Particularly, that the decrement in SAT rate reflects a slowing of search speed as a fixed, limited processing capacity is spread more diffusely over the items in the display.

5.2. Visual search and eccentricity

By deriving joint measures of discriminability and processing speed, we found that speed of information process-

ing was faster at peripheral than parafoveal locations for both search types. Processing speed was found to be about 90 (neutrally cued features) to 100 ms (neutrally cued conjunctions) faster when the stimuli were presented at 9° than at 4° eccentricity (Tables 1 and 2). As demonstrated in Carrasco et al. (2003), these speed differences are dissociable from target discriminability: Targets at 9° were only slightly more discriminable (higher asymptotic levels) than targets at 4° eccentricity, but they were processed at a substantially faster speed.

The visual system devotes a larger area and a greater number of neurons to the central visual field than to more peripheral regions, from the retinal ganglion cells to the visual cortex (DeValois & DeValois, 1988; Lennie, 1998; Livingstone & Hubel, 1987; Merigan & Maunsell, 1993; Shapley & Perry, 1986). Hence, a plausible explanation of the speed advantage for the periphery follows from an assumption that integration time increases with the size of the cortical area stimulated and the number of neurons involved in the computation (Hawken, Shapley, & Grosz, 1996).

Carrasco et al. (2003) evaluated this hypothesis by magnifying the stimuli so that they evoke a cortical representation with the same size, spatial frequency, and orientation differences between the target and distracters for both eccentricities. It was found that at the same eccentricity (9°), discriminability was better for the cortically magnified targets. Crucially, however, cortically magnified stimuli were processed about 40 ms slower than the unmagnified (original, standard) stimuli. Thus, magnified stimuli diminished, but did not eliminate, the temporal differences between standard stimuli presented at 4° and 9° eccentricity. This indicates that stimulating larger cortical regions results in slower processing, but the size of the stimulated area does not fully account for all of the observed temporal differences. Indeed, propagation of intracortical potentials may slow integration and processing time. Visual stimulation outside the classical receptive field (CRF) in V1 induces weak, longer-latency excitatory postsynaptic potentials (EPSPs), which scale with distance from the CRF, suggesting that integration of visual activation is spread by slow horizontal connections (Bringuier, Chavane, Glaeser, & Fregnac, 1999). Given that the computations necessary for orientation discrimination can occur in V1, propagation of horizontal connections in this area may be slow enough to account for a longer processing time (approximately tenths of milliseconds; Girard, Hupé, & Bullier, 2001).

Table 1 illustrates that the difference in processing speed brought about by eccentricity for both neutral and peripheral conditions is best captured by intercept differences, the minimum time (SAT intercept) necessary to discriminate the target's orientation. These differences in intercept were surprisingly stable, about 80 ms for the feature search and 100 ms for the conjunction search (Fig. 5; Table 1). This pervasiveness and rather stable effects of the stimulus eccentricity, despite differences in complexity between the

two tasks, suggests that the intercept might reflect early visual neurophysiological constraints.

The finding that differences in speed of processing as a function of eccentricity are manifested with stimuli and tasks of different complexity lends further support to the idea that the heightened responsiveness of the periphery to temporal properties (e.g., temporal resolution, flicker fusion, and motion detection) is partly due to the speed with which visual information is processed at different eccentricities (Carrasco et al., 2003). The differences in speed of processing as a function of eccentricity are substantial on the time scale of visual processing, both neurophysiologically and behaviorally. The observed differences are in fact comparable to estimates of the total time of a fast feed-forward sweep of activity, from retinal ganglion cells to parietal cortex in non-human primates (Lamme & Roelfsema, 2000). Behaviorally, for example, the human visual system extracts the information necessary to identify a word in the first 50 ms of fixating on a region (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981) and some complex processing of natural scenes can be achieved 150 ms after stimulus onset (Rousselet, Fabre-Thorpe, & Thorpe, 2002).

Feature and conjunction searches had similar processing characteristics across eccentricity. In terms of discriminability, both search types yielded a decrease in asymptote as set size increased for both eccentricities. This result replicates previous findings at 4° eccentricity (Carrasco & McElree, 2001). However, given that conjunctions are more complex than features (as they require the combination of two distinct features), at both eccentricities the rate was slower for conjunction search with set sizes 4 and 8 than for feature search (in which all set sizes were best fit to one rate). The rate parameter was similar for conjunction search with set size 1 and for feature search. This is not surprising because when a target appears by itself in an orientation discrimination conjunction search task, it is essentially equivalent to a feature search. This pattern of results is also consistent with our previous findings (Carrasco & McElree, 2001).

5.3. Covert attention and eccentricity

Discriminability decreased as set size increased, for both feature and conjunction searches. Tables 1 and 2 show that precueing the target location virtually eliminated the set size effect for both feature and conjunction searches at both eccentricities. These results replicate previous findings at 4° eccentricity (Carrasco & McElree, 2001).

Directing attention to the target location also accelerated processing speed, a result that was also consistent with previous findings (Carrasco & McElree, 2001; Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004). This attentional effect was best captured in the rate parameter. As mentioned earlier, more research is needed to specify the precise mechanism by which attention speeds the processing of visual information. Covert attention may serve

to boost the rate at which target information is acquired directly or, alternatively, may speed overall processing by enabling the observer to exclude irrelevant information. These alternative explanations are not mutually exclusive. Given that we observed increases in the rate of processing in both conjunction searches, as well as in feature searches where capacity limits are nonexistent (Palmer, 1994) or minimal (McElree & Carrasco, 1999), as well as when the target appears by itself or accompanied by distracters, our data support the hypothesis that attention can speed the uptake of target information.

Although attention sped processing, it did not attenuate the effects of eccentricity on processing speed differences. For the feature search, precueing the target location sped processing by about 50 ms at both eccentricities (Table 2). For the conjunction search, the difference in processing time increased with set size, ranging from about 20–115 ms at both eccentricities (Table 2). Interactions between target and distracters may underlie this increasing effect. Note that the cortical representation for stimuli presented parafoveally (4°) is not only larger for each stimulus than that for stimuli presented peripherally (9°), but the interstimulus distance at the cortical level decreases as well. Thus, the more distracters, the higher the probability of lateral interactions and crowding (Carrasco & Frieder, 1997; Pelli, Palomares, & Majaj, 2004).

Crucially, for both feature and conjunction searches, the speed differences due to eccentricity were independent of attentional allocation. In both cueing conditions, the difference in speed at different eccentricities was about 80 ms for features, and about 100 ms for conjunctions (Table 2, right most column). Consequently, our results suggest that attention does not have a compensatory effect on speed of processing across eccentricity. Instead, attention speeds processing to the same degree at both parafoveal and peripheral eccentricities.

The lack of a compensatory effect is surprising in light of the finding that attention increased speed of processing more at iso-eccentric locations where processing is slower (i.e., at the North location of the vertical meridian) than at the locations where processing is faster (i.e., along the horizontal meridian of the visual field; Carrasco & Giordano et al., 2004; Carrasco & Ling et al., 2004). This inconsistency is difficult to explain at the present time because we do not have a good understanding of the mechanisms by which attention speeds processing. Attention does increase contrast sensitivity (e.g. Carrasco et al., 2000; Ling & Carrasco, 2006; Lu & Dosher, 1998; Solomon et al., 1997), and speed of processing increases with stimulus contrast (Albrecht, 1995; Carandini, Heeger, & Movshon, 1997). However, the effects of attention on temporal dynamics are unlikely to be due to increased contrast alone. Increasing stimulus contrast accelerates information processing (Albrecht, 1995; Carandini et al., 1997), but to a lesser extent than attention. This suggests that attention is doing more than merely enhancing contrast sensitivity. Moreover, the effect of attention on discriminability, which may be related

to contrast sensitivity, is more pronounced for conjunction than for feature searches (Carrasco & McElree, 2001; Carrasco & Yeshurun, 1998), and when targets appear at farther eccentricities (Carrasco et al., 2002; Carrasco & Yeshurun, 1998). However, the effects of attention on temporal dynamics are very similar for both search types and at different eccentricities.

5.4. Summary

The time-course data show that information is processed faster at peripheral than parafoveal locations, and that attention speeds information processing by a surprisingly constant amount at different eccentricities in search tasks of differing complexity. Although it is not well understood how attention modulates processing speed, both facts appear to provide important constraints for theorizing about the relation between attention and temporal dynamics of visual perception.

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