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Temporal performance fields: visual and attentional factors

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Abstract

This study is the first to investigate: (a) 'temporal performance fields,' whether the speed of information accrual differs for different locations at a fixed eccentricity, and (b) whether covert attention modulates temporal dynamics differentially at isoeccentric locations. Using the speed accuracy tradeoff (SAT) procedure, we derived conjoint measures of how isoeccentric locations and precueing targets location affect speed and accuracy in a search task. The results demonstrate the existence of temporal performance fields, analogous to spatial performance fields: information accrual was fastest for target on the horizontal meridian, intermediate for targets at the intercardinal locations, slow for targets on the vertical meridian, and slowest for targets at the North (N) location (accrual time pattern: E&W < intercardinal < S < N). Surprisingly, in contrast to spatial performance fields, where covert attention enhanced discriminability at all locations to a similar degree, attention differentially sped up processing at the slower locations, with a greater benefit evident along the vertical than the horizontal meridian, particularly at the N location, and an intermediate benefit at intercardinal locations (viz., N > S > intercardinal > E&W). Hence, the compensatory effect of attention eliminated the temporal asymmetries across isoeccentric locations.
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1. Temporal performance fields: visual and attentional factors

Discriminability decreases with eccentricity in many visual tasks, but covert attention has the inverse effect. Covertly allocating attention to a location enhances discriminability, and the magnitude of this effect increases with eccentricity (Carrasco, Williams, & Yeshurun, 2002; Carrasco & Yeshurun, 1998; Yeshurun & Carrasco, 1998, 1999, 2000). These findings suggest that covert attention provides the most help at locations where it is most needed. However, this does not appear to be a general principle. Discriminability also varies at different locations at a fixed eccentricity, but covert attention affects all isoeccentric locations to a similar degree (Cameron, Tai, & Carrasco, 2002; Carrasco, Talgar, & Cameron, 2001; Talgar & Carrasco, 2002).

The beneficial effects of covert attention are not limited to merely enhancing discriminability. Covert attention also speeds information accrual (Carrasco &

McElree, 2001). Consequently, to fully characterize how attention affects information processing across the visual field, it is essential to examine both spatial and temporal dimensions of performance. In this study, we first document the existence of a 'temporal performance field' by showing that the rate of information accrual varies for different locations at a fixed eccentricity. We then show that covertly attending to different isoeccentric locations speeds information accrual in a manner that effectively eliminates inherent differences in visual information uptake among the locations. These findings suggest that attention has the same compensatory effect on temporal dynamics at a fixed eccentricity as it does on discriminability across different eccentricities.

1.1. Performance fields

The term 'performance fields' is used to describe the fact that discriminability is not homogeneous at isoeccentric locations (Altpeter, Mackeben, & Trauzettel-Klosinski, 2000; Mackeben, 1999). Better performance is evident on the horizontal than vertical meridian of the visual field. This horizontal–vertical anisotropy (HVA), as it has been termed, has been reported in a variety of visual tasks (e.g., Carrasco & Frieder, 1997; Mackeben,

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1999; Rijsdijk, Kroon, & van der Wilt, 1980; Rovamo & Virsu, 1979), including measures of contrast sensitivity (Cameron et al., 2002; Carrasco et al., 2001; Rijsdijk et al., 1980) and spatial resolution (Carrasco et al., 2002; Nazir, 1992; Regan & Beverley, 1983; Talgar & Carrasco, 2002) in detection, discrimination and localization tasks. Additionally, there is evidence for a vertical asymmetry, with findings that performance is better in the lower than upper regions of the visual field (e.g., Edgar & Smith, 1990; Gordon, Shapley, Patel, Pastagia, & Truong, 1997; Previc, 1990; Rubin, Nakayama, & Shapley, 1996). This asymmetry seems to be driven by a vertical meridian asymmetry (VMA, better performance in the location directly below fixation than directly above), which has been shown in measures of both contrast sensitivity (Cameron et al., 2002; Carrasco et al., 2001) and spatial resolution (Carrasco et al., 2002; Talgar & Carrasco, 2002). Both asymmetries become more pronounced as eccentricity, spatial frequency, and the number of distractors increase in a wide range of tasks (e.g., orientation discrimination, detection and localization) with different stimulus orientation and luminance levels, with both monocular and binocular viewing conditions, and with or without a local post-mask (Carrasco et al., 2001, 2002). At intercardinal locations (NE, NW, SE and SW) performance levels fall between those for locations on the horizontal and vertical meridians (Cameron et al., 2002; Carrasco et al., 2001).

Given the existence of spatial performance fields (Cameron et al., 2002; Carrasco et al., 2001; Mackeben, 1999) and, as outlined below, that temporal dynamics differ as a function of eccentricity, with processing being faster at peripheral than central locations (Carrasco, McElree, Denisova, & Giordano, 2003), we hypothesized that inhomogeneities may also exist in temporal aspects of processing. The first goal of this study was to determine whether "temporal performance fields" exist, or, conversely, whether information accrues at the same speed at isoeccentric locations that differ in discriminability. If temporal inhomogeneities do exist, it is by no means obvious how they might pattern. Given that the visual system has developed a duplex design to meet conflicting environmental demands, with the fovea having the resolution needed to process fine spatial information and the periphery being more sensitive to temporal properties (e.g., DeValois & DeValois, 1988; Hartmann, Lachenmayr, & Brettel, 1979; McKee & Nakayama, 1984), the visual system may process information faster at isoeccentric regions with poor discriminability. Indeed, discriminability decreases but the speed of information accrual increases with eccentricity (Carrasco et al., 2003). Alternatively, one could hypothesize that information processing is privileged at certain locations both in terms of discriminability and temporal dynamics, with information being processed faster at isoeccentric regions with higher discriminability.

1.2. Covert attention

Whenever we open our eyes, we face an overwhelming amount of visual information. Our capacity to process this information is limited by the high-energy cost of the neuronal activity involved in cortical computation (Lennie, 2003). Selective attention enables us to transform the vast amount of visual input into comprehensible units by selecting relevant information from irrelevant noise. Central to this notion is that a single retinal stimulus can be processed in different ways. Attention allows us to select a location or aspect of the visual scene and to prioritize its processing. Attention can be allocated overtly, by directing gaze towards a location of the visual scene, or covertly, by attending to an area in the periphery without actually directing one's gaze towards it. The second goal of this study was to determine whether covert attention modulates any potential differences in the speed of processing at isoeccentric regions.

A growing body of behavioral evidence demonstrates that there are two components of attention: 'sustained' and 'transient.' The first corresponds to the common intuition that we can monitor at will information at a given location; e.g., in driving, where we often decide to monitor relevant information in different locations while keeping our eyes on the road. Transient attention corresponds to a faster, more automatic and involuntary allocation of attention to a location where sudden stimulation has occurred; e.g., when driving, a ball rolling out into the street will instantly grab attention. These systems follow different time courses and can be triggered with different cues: a sustained, central or endogenous cue presented in the center of the visual field can direct attention in a conceptually-driven fashion in ∼300 ms, whereas a transient, peripheral or exogenous cue presented adjacent to the relevant location captures attention in a stimulus-driven automatic manner in ∼100 ms (Cheal & Lyon, 1991; Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). That shifts of attention by sustained cues appear to be under conscious control, and that peripheral cues capture attention in an automatic manner, is consistent with several findings: (a) peripheral cues result in faster reaction times (RTs) than central cues; (b) performance directed by relevant central cues can be impaired by irrelevant peripheral cues; (c) performance at peripherally cued locations is facilitated even when observers are instructed to ignore the peripheral non-informative cues (Müller & Rabbitt, 1989; Posner, 1980; Posner & Cohen, 1984; Yantis, 1996).

Transient covert attention has been found to improve discriminability in a variety of early visual tasks, such as

contrast sensitivity (Cameron et al., 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lu & Dosher, 1998; Solomon, Lavie, & Morgan, 1997), acuity (Carrasco et al., 2002; Shiu & Pashler, 1995; Yeshurun & Carrasco, 1999), hyperacuity (Balz & Hock, 1997; Mackeben & Nakayama, 1993; Yeshurun & Carrasco, 1999); orientation discrimination (Baldassi & Burr, 2000; Morgan, Ward, & Castet, 1998), texture segmentation (Yeshurun & Carrasco, 1998, 2000; Talgar & Carrasco, 2002), and visual search (Cameron, Tai, Eckstein, & Carrasco, 2004; Carrasco & Yeshurun, 1998; Nakayama & Mackeben, 1989). In addition, with the response–signal speed-accuracy tradeoff (SAT) procedure (see below), we have shown that transient attention not only improves discriminability but also accelerates the speed of information accrual at a cued location in both feature and conjunction searches (Carrasco & McElree, 2001). By improving discriminability, covert 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.

1.3. Effects of covert attention on performance fields

Some have attributed performance differences across the visual field to attention (Altpeter et al., 2000; He, Cavanagh, & Intrilligator, 1996; Mackeben, 1999). However, these studies have neither ruled out the visual factors underlying these heterogeneities nor explicitly manipulated attention. As has been established in visual search (e.g., Carrasco, Evert, Chang, & Katz, 1995, 1998; Carrasco & Frieder, 1997; Geisler & Chou, 1995; Verghese & Nakayama, 1994), it is essential to rule out explanations based on visual constraints before invoking less well-defined constructs like attention.

In studies that have systematically manipulated attention and several visual factors (e.g., target eccentricity, spatial frequency and stimulus orientation), attention has been found to enhance contrast sensitivity (Cameron et al., 2002; Carrasco et al., 2001) and spatial resolution (Carrasco et al., 2002; Talgar & Carrasco, 2002) in discrimination, detection and localization tasks. However, the effect of attention is so similar at all iso-eccentric locations in the visual field that it does not affect the shape of the performance field. Fig. 1 illustrates this point: when a target location is precued, the contrast necessary to attain the same performance level (82% correct) in an orientation discrimination task is significantly lower (bottom panel) than when the target location is not precued (top panel). Nevertheless, the magnitude of the cue effect is similar at all locations, so the shape of the performance fields is not altered. This suggests that the discriminability differences evident in the performance fields cannot be reduced to attentional differences.
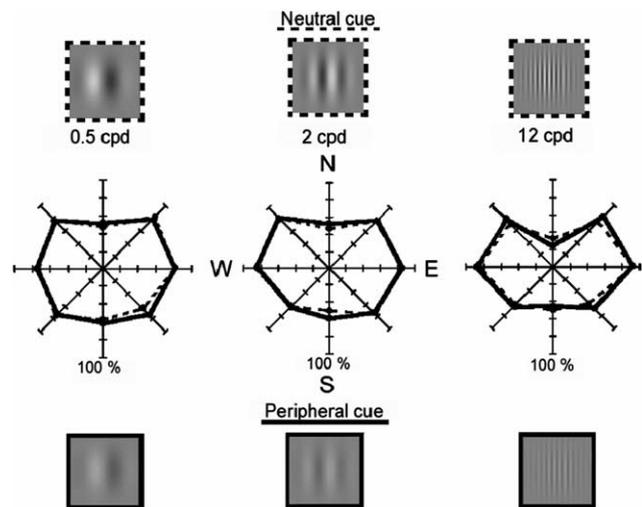

Fig. 1. Spatial performance fields. This figure illustrates that to attain a constant overall performance level (82%) less contrast is needed when a peripheral cue precedes the target (bottom squares) than when a neutral cue does (top squares). The contrast differences depicted in the Gabor patches are based on data reported by Carrasco et al. (2000). The radial graphs depict performance at each of 8 locations. As spatial frequency increases (from left to right), the HVA (E&W vs. N&S) and VMA (N vs. S) become more pronounced. Note that the shape of the performance field remains the same in the presence and absence of a peripheral cue. These radial graphs are based on data reported by Carrasco et al. (2001).

Beyond simply examining whether there are differences in the speed of information accrual at isoeccentric locations, the second goal of this study was to determine whether covert attention alters temporal performance fields by speeding up processing differentially at attended locations within a fixed eccentricity. A priori, it is again not obvious how covert attention may alter potential differences in processing speed. Extrapolating from findings that covert attention does not alter spatial performance fields, one could hypothesize that covert attention would speed processing at all isoeccentric locations to the same degree. However, extrapolating from findings in many visual tasks that discriminability decreases but the beneficial effect of covert attention increases with eccentricity (Carrasco et al., 2002; Carrasco & Yeshurun, 1998; Yeshurun & Carrasco, 1998, 1999, 2000), one could hypothesize that the effect of covert attention may be more pronounced at the least privileged locations thus attenuating or eliminating temporal differences.

1.4. SAT procedure: discriminability and temporal dynamics

In this study, we used the SAT procedure to obtain separate estimates of discriminability and processing speed for different locations at a fixed eccentricity, and compared performance when transient attention was directed to the target location via a peripheral cue to

when attention was distributed via a neutral cue. Given that discriminability varies at isoeccentric locations (Cameron et al., 2002; Carrasco et al., 2001) and that covert attention enhances discriminability (e.g., Baldassi & Burr, 2000; Carrasco et al., 2000, 2002; Lu & Dosher, 1998), it is essential to use a procedure that enables the measurement of the speed of information processing in circumstances in which discriminability varies (Carrasco & McElree, 2001; McElree & Dosher, 1989; Reed, 1973; Wickelgren, 1977). By providing separate estimates of discriminability and processing time, the SAT procedure enabled us to precisely measure processing speed while concurrently assessing the effects of location and covert attention on discriminability.

Standard response time measures (e.g., simple or choice RT) are insufficient for this purpose, as response time differences can be due to differences in decision criteria or discriminability rather than differences in the speed of information processing (Dosher, 1979; McElree & Dosher, 1989; Ratcliff, 1978; Reed, 1973; Wickelgren, 1977). For example, models of response time (e.g., Ratcliff, 1978) typically assume a response is executed when information accumulation exceeds a criterion value. A response threshold can be reached at an earlier point in time if the criterion is lower in one condition than in another, or if the stimulus in one condition is more discriminable than another, even if the speed of information accrual is the same in both conditions. A solution to this problem is to employ the response–signal SAT procedure (Reed, 1973), which controls for tradeoffs and provides conjoint measures of discriminability and information accrual.

1.5. SAT analysis of visual search

The SAT procedure provides conjoint measures of speed and accuracy by enabling the construction of a full time-course function describing how discrimination varies with processing time. Time-course functions are derived by requiring observers to respond immediately to a response signal (tone) presented at one of several times after the onset of the display. By sampling a suitable range of times, the full time course of processing can be measured, which includes periods when discrimination is at chance levels, periods during which discrimination performance increases, and periods when discrimination has reached its maximum or asymptotic level.

Fig. 2 displays hypothetical functions for two arbitrary conditions and serves to illustrate how this procedure provides measures of both discriminability (top panel) and processing dynamics (bottom panel). The top panel illustrates what is expected if conditions differ in discriminability alone. Here, the functions rise to different levels of asymptotic discriminability but are associated with the same intercept (point when dis-
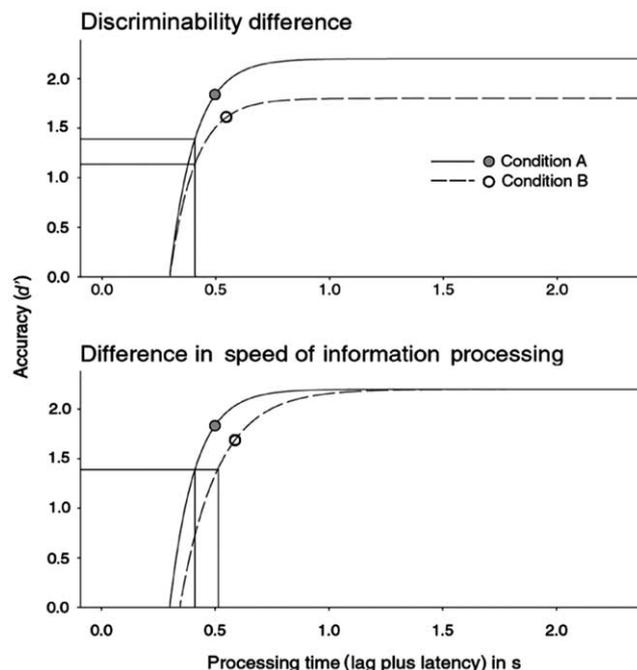

Fig. 2. Hypothetical SAT functions. Illustrative SAT functions (after Dosher, 1982), plotted in d' units ($\sqrt{2}$ of the standard normal deviate of the probability of correctly judging the target's orientation) vs. processing time (time of the response cue plus observer's average latency to respond). (Top panel) expected pattern if an experimental factor (e.g., attention or location) 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. (Bottom panel) one expected pattern if the factor alters the speed of information accrual (intercept and rate) without a concomitant effect on discriminability. The intercept ($d' = 0$) measures the minimal time needed for above-chance discrimination. The circles show the corresponding RT points in SAT coordinates, illustrating that RT differences can arise from differences in either discriminability (top panel) or dynamics (bottom panel).

crimination departs from chance) and proportional rates of information accrual. The bottom panel illustrates conditions that differ in processing speed, with Condition A being faster than Condition B. Underlying differences in processing speed will engender differences in either the intercept of the SAT function, the rate at which the function approaches asymptote, or both parameters (as illustrated in the bottom panel). 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. 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. 2 show the time when the functions reach the $1 - 1/e$ (63%) point. In the top

panel, where the processing speed is identical, the functions reach this point at the same time as indicated by the vertical line. In the bottom panel, where the functions are associated with a common asymptote but different rates and intercepts, the $1 - 1/e$ point is reached at different times.

To further illustrate why standard RT differences may not reflect true speed differences, the circles on the functions in Fig. 2 show corresponding response time points in SAT coordinates that might be observed in an analogous response time variant of the task. The position of the response time points on the corresponding SAT functions is determined by the decision criteria that an observer uses to balance speed and accuracy. Direct comparisons of observers' RTs and SAT functions have shown that in an RT procedure observers typically respond at sub-asymptotic times, often close to the two-thirds point as shown in this figure (Dosher, 1982; McElree & Dosher, 1993; Reed, 1973). The points in the panels illustrate that the same difference in response time can arise from differences in either discriminability (top panel) or dynamics (bottom panel). Empirically, response time has been shown to vary with asymptotic SAT differences alone (e.g., Dosher, 1982; McElree & Carrasco, 1999; McElree & Dosher, 1989), with dynamics differences alone (e.g., Dosher, 1981; McElree & Griffith, 1995), and with both asymptotic and dynamics differences (e.g., Carrasco et al., 2003; McElree, 2002; McElree & Carrasco, 1999; McElree & Dosher, 1993).

The SAT method has been used to investigate the time-course of rapid mental processes in several domains, including memory (e.g., Dosher, 1981, 1982; McElree & Dosher, 1989, 1993; Ratcliff, 1978; Reed, 1973) and language comprehension (e.g., McElree, 1993; McElree & Griffith, 1995, 1998). More recently, this procedure has been used to investigate various aspects of visual search (Carrasco & McElree, 2001; Carrasco et al., 2003; McElree & Carrasco, 1999). For instance, we used the SAT procedure to test time-course predictions for serial self-terminating and parallel models of visual search. The SAT analysis demonstrated that parallel models provide a better account of both feature and conjunction data (McElree & Carrasco, 1999).

Two recent SAT studies are particularly relevant to the present issues in that they assessed (a) temporal dynamics at varying locations across the visual field, although at heteroeccentric rather than isoeccentric locations, and (b) the effects of covert attention on information accrual. By deriving joint measures of discriminability and speed, Carrasco et al. (2003) investigated whether the periphery's heightened sensitivity to temporal properties (e.g., DeValois & DeValois, 1988; Hartmann et al., 1979; McKee & Nakayama, 1984) is partly due to the speed with which information is processed at different eccentricities. We reported the first

behavioral evidence showing that decreasing eccentricity or enlarging stimulus size engendered slower temporal dynamics. In another study, Carrasco and McElree (2001) used the SAT procedure to contrast discriminability and processing speed when a target location was peripherally precued or not. The SAT time-course profiles showed that covert attention improves discriminability, but crucially also speeds up information accrual at the attended location.

2. Experiment

To characterize temporal performance fields and to assess whether covert attention affects the speed of information processing differentially at attended locations within a fixed eccentricity, we presented stimuli in eight possible locations at 4° or 9° eccentricity. Observers performed an orientation feature search task. We used Gabor patches (suprathreshold sinusoidal gratings vignetted by a Gaussian envelope) that are well matched to early linear spatial filters in the visual system. In a two-alternative forced choice discrimination, observers indicated whether a two cycle per degree (cpd) Gabor target was tilted to the left or right (Fig. 3).

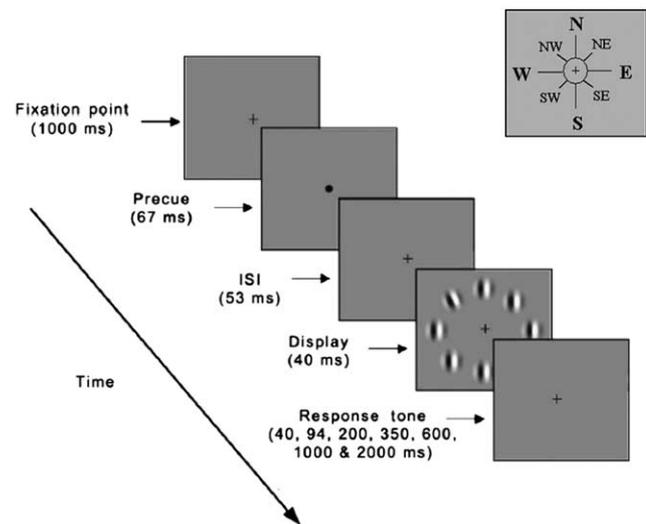**Response-signal speed-accuracy trade-off procedure**

Fig. 3. Sequence of events in a single trial. The stimuli were randomly presented at eight equidistant locations from a central fixation point on an invisible polar grid at either 4° or 9° eccentricity. The compass indicates specific locations in the display. The interval between the cue onset and the stimulus onset was optimum to facilitate transient attention (e.g., Nakayama & Mackeben, 1989); the interval between the cue onset and stimulus offset was brief enough to prevent goal or target directed eye movements (e.g., Mayfrank, Kimmig, & Fischer, 1987). Observers were required to respond whether the target was tilted to the right or the left within 350 ms of the response tone presented at one of seven times after stimulus onset. Feedback was provided after each trial and block.

We manipulated transient attention by presenting a peripheral precue adjacent to the target location on a random half of the trials. This precue indicated display onset and target location but did not signal the target orientation (Carrasco et al., 2000, 2001, 2002; Nakayama & Mackeben, 1989; Yeshurun & Carrasco, 1998, 2000). A neutral precue was presented on the remaining trials indicating display onset and that the target had equal probability of appearing at any of the eight locations. To measure discriminability and information accrual conjointly, a tone sounded at one of seven times ranging from 40 to 2000 ms after the display onset. 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.

3. Methods

3.1. Observers

Ten NYU students participated in this experiment. All (but one, AMG) 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 in. IBM P260 monitor (1024×768; 120 Hz)—thus providing a larger possible set of distinct luminance levels ($\sim$12.6 bits). Background luminance was set to the middle of the monitor's range (16 cd/m^2).

3.3. Stimuli and design

Gabor patches that varied in orientation subtended 2° of visual angle (full width at $1/e$), on the basis of a fixed 114 cm viewing distance. A small fixation dot ($0.2 \times 0.2°$ of visual angle) was presented at the center of the screen throughout the experiment. The stimuli were randomly presented at eight equidistant locations (at the cardinal and intercardinal locations) from a central fixation point on an invisible polar grid at 4° or 9° eccentricity (Fig. 3).

All gratings had a center spatial frequency of 2 cpd. In this feature search task, the target stimulus was a tilted (30° clockwise or counterclockwise) patch, presented either in isolation or with seven distractors of vertical orientation. Before testing, stimulus contrast was adjusted for each observer so that performance

across all intervals was at the 80–85% correct level (contrast ranged from 8% to 16% across observers).

It is known that 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 (Azzopardi, Jones, & Cowey, 1999; DeValois & DeValois, 1988; Lennie, 1998). We magnified the size (Virsu & Rovamo, 1979), spatial frequency (Virsu & Rovamo, 1979), and orientation (Makela, Whitaker, & Rovamo, 1993) of the stimuli presented at 9° so that they would evoke the same cortical representations as the stimuli at 4° eccentricity. The resulting parameters were: size = 3.6°, spatial frequency = 1.1 cpd, and orientation for tilted items = 37.4°.

3.4. Procedure

Attention was directly manipulated by presenting, on a random half of the trials, a peripheral precue (small circle, $0.3 \times 0.3°$ of visual angle, at 2° from the center of the target), which appeared for 67 ms to indicate display onset and location, but not the orientation of the target. The remaining trials contained a neutral cue (a small circle at the center of the display) indicating display onset but providing no information about either the location or the orientation of the target. As illustrated in Fig. 3, the Gabor patches with 0 or 7 distractors appeared for 40 ms after an interstimulus interval (ISI) of 53 ms. The interval between cue and target onsets maximized the attentional benefit, which occurs at about 80–120 ms (Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Given that 200–250 ms are needed for a saccade to occur (Mayfrank et al., 1987) the interval between the cue onset and the stimulus offset was brief enough to prevent goal or target directed eye movements. Observers were asked to respond whether the target was tilted to the right or to the left. To implement the SAT procedure, a response tone was presented after the target display at seven time lags ranging from 40 to 2000 ms after display onset. Observers were instructed and trained to respond within 350 ms of the response tone, whether or not they had fully processed the display. Feedback was provided after each trial to indicate whether observers responded during the allotted response window.

All variables—cue type: neutral vs. peripheral; set size: 1 or 8; and response tone: 40, 94, 200, 350, 600, 1000 and 2000 ms—were randomly presented within each block of trials. All observers completed 1 practice session to accustom themselves to the task, particularly to the deadline procedure. Three observers completed 10 experimental sessions and another 4 observers completed 7 sessions, each consisting of 8 blocks of 112 trials, with a total of 896 randomized trials per session at 4° eccentricity. Four observers conducted this experi-

ment with magnified stimuli at 9° eccentricity, one of whom (AMG) also participated in the 4° condition.

4. Results

The time course data for each observer and for the average over observers were fit with an exponential approach to an asymptote:

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

In Eq. (1), 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. The parameters of Eq. 1 provide a quantitative summary of the shape of the SAT function (Reed, 1973; Wickelgren, 1977), and provide estimates of discriminability (λ) and processing speed (β and δ).

4.1. Exponential fits

A nested model-testing scheme was used to determine how the experimental factors (2 set sizes × 2 cueing conditions) affected the three parameters of Eq. 1 at each of the eight relevant locations. The three parameters of the exponential equation were fit to each observer's data and the average data. We evaluated a range of models between the extremes of a null model, in which the functions of interest were fit with a single asymptote (λ), rate (β), and intercept (δ), and a fully saturated model in which each function was fit with a unique set of parameters. Because asymptotic accuracy in the neutral condition varied with set size (with accuracy being 0.30 d' units higher with set size of 1 as compared to 8) and with attentional cueing in comparisons across the neutral and cued conditions (with accuracy being 0.22 d' and 0.48 d' units higher when target location was peripherally cued for set sizes 1 and 8, respectively), model fits required allocating separate asymptotic parameters to both factors, and fits that ignore these differences systematically misfit the data and produced uniformly poor R^2 values. Consequently, competitive model tests largely focused on dynamic differences, examining whether there were differences in rate, intercept or both parameters, across conditions. The quality of fit was determined by three criteria: (1) the value of an adjusted-R^2 statistic, where the proportion of variance accounted for by a model was adjusted by the number of free parameters (Reed, 1973); (2) the consistency of parameter estimates across observers, which was assessed by standard statistical tests (e.g., paired samples t-tests) on the parameter estimates; and (3) an evaluation of whether any fit left systematic
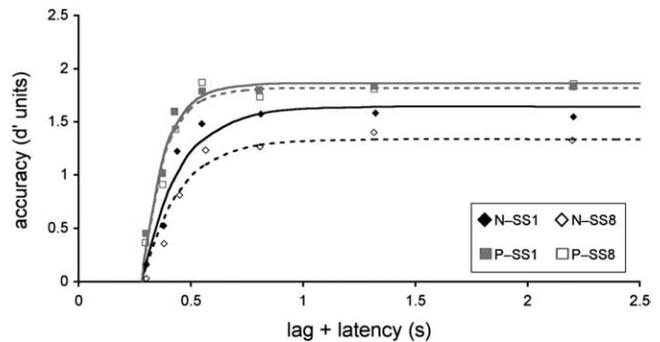

Fig. 4. Results across location. Average (over observers and location) discrimination accuracy (in d' units) as a function of processing time at 4° eccentricity. Smooth functions show the best-fitting exponential model (Eq. 1) for the cued (squares) and neutral (diamonds) conditions, based on fits of nested models that systematically varied the three parameters of Eq. 1 ($R^2 = 0.95$). See Table 1 for model parameter estimates.

residuals that could be accounted for by additional parameters.

Parameter estimates for the best fitting model (4 asymptotes × 2 rates × 1 intercept; $R^2 = 0.95$) to the data averaged across observers and across locations are shown in Fig. 4 and Table 1.

4.2. Overall performance

The group average time-course functions for 4° eccentricity in the neutral condition (i.e. when the target location was not cued) are displayed in Fig. 4. Model fits demonstrated that set size affected discriminability but not processing speed (β or δ parameter). When either rate or intercept was varied with set size, R^2 values did not increase and the parameter estimates did not show any systematic trend across observers. These findings replicated our previous results (Carrasco & McElree, 2001; Carrasco et al., 2003; McElree & Carrasco, 1999). Asymptotic discriminability (λ) decreased as set size increased from 1 to 8, by 0.30 d' units ($p < 0.005$, ranging from 0.13 to 0.52 for individual observers). The observed reduction in asymptotic discriminability with larger set sizes is consistent with several "confusability" accounts of visual search (e.g., Eckstein, 1998; Kinchla,

Table 1
Best fitting model parameters for average SAT function (across observers and locations) shown in Fig. 4

	Neutral	Peripheral
Discriminability (λ in d' units)		
Set size 1	1.64	1.86
Set size 8	1.34	1.82
Processing speed (ms)		
Rate (β for all set sizes)	61	103
Intercept (δ for all set sizes and cue types)	280	280

1992; Palmer, 1994), as the signal-to-noise ratio decreases with number of distractors, leading to an increased likelihood of a decision error.

The group average time-course functions for 4° eccentricity when the target location was precued are also displayed in Fig. 4. Consistent with previous studies (Carrasco & McElree, 2001; Carrasco et al., 2003; McElree & Carrasco, 1999), model fits indicated that set size did not affect the speed of processing. Also consistent with previous results (Carrasco & McElree, 2001), precueing the target location: (a) improved discriminability by 0.22 (from 1.64 to 1.86) d' units for set size 1 and by 0.48 (from 1.34 to 1.82) d' units for set size 8. This improvement attenuated set-size discriminability difference by 0.26 ($p < 0.001$; ranging from 0.02 to 0.43 for individual observers) from 0.30 to 0.40 d' units for set sizes 1 and 8; (b) sped information processing by 68 ms ($p < 0.001$; ranging from 25 to 80 ms for individual observers), from 447 to 379 ms. For individual observers, differences in processing speed were best captured in rate, although these differences could also be captured in intercept. In these circumstances, differences in processing speed are best contrasted with a composite measure, $\delta + \beta^{-1}$, which gives an average processing time in millisecond units. This measure also 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 enables cross-condition comparisons when rate and intercepts are not constrained to be equal across the conditions of interest (Table 1).

4.3. Performance fields

We first report how discriminability varied with location—spatial performance fields—which replicate our previous findings, and then report the new results on how the speed of processing varied at different locations at 4° eccentricity—temporal performance fields.

4.3.1. Spatial performance fields

Consistent with previous findings: (1) performance was not homogeneous across the visual field; rather, it was better along the horizontal meridian (E&W) than at intercardinal locations, which was better than along the vertical meridian; (2) precueing target location improved overall discriminability and diminished the difference in d' for set sizes 1 and 8 (Carrasco & McElree, 2001), but did not change the shape of the performance field (Cameron et al., 2002; Carrasco et al., 2001, 2002; Talgar & Carrasco, 2002).

Unfortunately, discriminability at 9° eccentricity for both standard and magnified stimuli was too low ($d' < 1$) and the goodness of fit measures were also too low ($R^2 \sim 0.5$) to yield accurate estimates of temporal dynamics at the vertical meridian, especially at the N

location. This was the case even for a trained observer (AMG) who participated in both eccentricity conditions. This result is in line with the finding that spatial performance fields become more pronounced as eccentricity increases (Carrasco et al., 2001, 2002), to the point that with the same stimulus contrast we could not capture reliable performance at all locations for SAT analysis of performance fields. Increasing stimulus contrast to improve discriminability at this eccentricity would result in unreliable estimates of temporal dynamics at the horizontal meridian, where discriminability was already high ($d' > 2.5$); performance would have been high even at the short response lags, where it should be at chance in order to capture the full time-course of processing.

4.3.2. Temporal performance fields

To estimate processing speed and accuracy at each of the 8 locations, the data for each observer and the average across observers was fit with a 4 asymptotes × 1 rate × 2 intercepts model, which was found to yield the best fit to the average performance across locations. This model allocated a separate intercept to the two cueing conditions to capture the effect that peripheral cueing has on processing speed. Fig. 5 presents the fits to the average across observers for the cardinal locations. The differences in dynamics evident in this figure could also be expressed as a difference in rate for most locations except for those along the vertical meridian, where a 4-1-2 model provided a substantially better fit. As with the average across location data, we summarized temporal differences with the composite measure ($\delta + \beta^{-1}$) to avoid parameter tradeoffs and to directly enable cross-location comparisons.

Two novel findings emerged from this analysis. First, the speed of information processing was significantly different at isoeccentric locations. Fig. 6 presents the composite measures for each of the 8 locations. When the stimuli appeared at the E or W locations, the composite speed measure was found to be ∼30 ms faster than when the stimuli appeared at the S location. The S location was ∼30 ms faster than the N location, and the speed at intercardinal locations was between that for the horizontal and vertical meridians. In the average data, the HVA was ∼46 ms (significant across observers, $p < 0.01$) and the VMA was ∼27 ms ($p < 0.01$), but at the horizontal meridian there was no difference between E and W (3 ms, $p > 0.10$). This pattern of results was present in all observers. Second, in contrast to the remarkably similar precueing benefit in discriminability at all isoeccentric locations (Cameron et al., 2002; Carrasco et al., 2001, 2002; Talgar & Carrasco, 2002), precueing sped information accrual in all locations but more so at the slow ones. The benefit was most pronounced at the slowest location, the N location (85 ms), followed by the S location (64 ms), the intercardinal
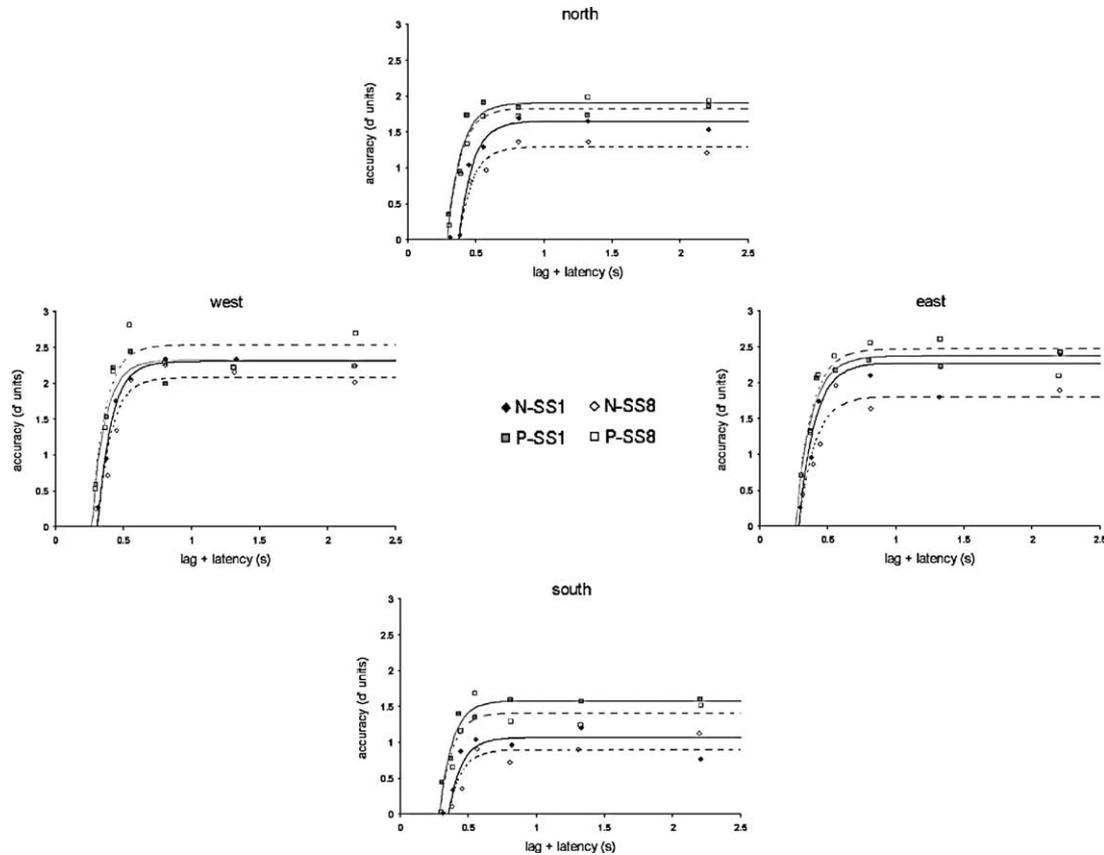
Fig. 5. Results per cardinal location. Average (over observers) discrimination accuracy (in d' units) as a function of processing time at 4° eccentricity for each cardinal location. Smooth functions show the best-fitting exponential model (Eq. 1) for the cued (squares) and neutral (diamonds) conditions, based on fits of nested models that systematically varied the three parameters of Eq. 1 (North: $R^2 = 0.95$, East: $R^2 = 0.92$, South: $R^2 = 0.87$, West: $R^2 = 0.90$).[1]

locations (on average 52 ms), and finally the locations at the horizontal meridian (on average 35 ms). In sum, the HVA was reduced from 46 to 8 ms ($p < 0.001$) and the VMA was reduced from 27 to 6 ms ($p < 0.01$). These results indicate that precueing functionally eliminated the temporal asymmetries.

In order to isolate and compare the speed differences for each of the cardinal locations, accuracy was normalized by asymptote, estimated by model fits, and percent of asymptote was plotted as a function of time. The fact that set size does not affect speed of information accrual at isoeccentric locations is reflected in the fact that the graphs for set size 1 and 8 are virtually the same for each of the neutral and peripheral conditions.

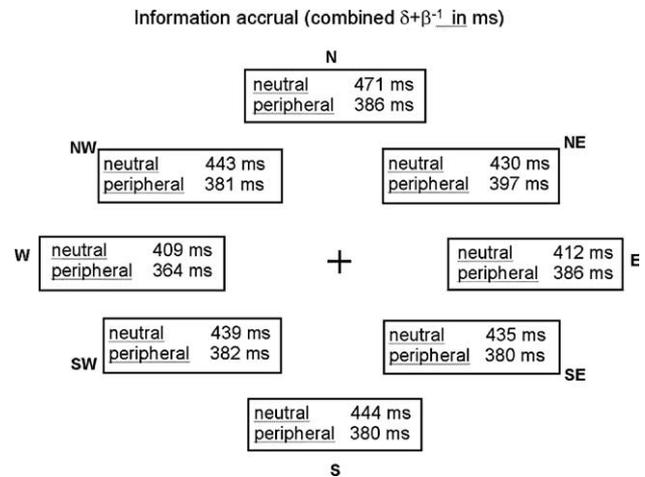In the neutral graphs (Fig. 7a and c), at 350 ms (indicated by the red patterned horizontal lines), E and

Fig. 6. Information accrual at each location. The speed of information accrual was calculated for each location by combining parameter estimates of rate and intercept ($\delta + \beta^{-1}$, estimated from the best-fitting exponential model). As illustrated here, there exists a temporal performance field that parallels the spatial performance fields (E&W > IC > S > N). Here, however, attention attenuates and practically eliminates the differences in accrual rates, suggesting that attention does not affect speed of processing uniformly at isoeccentric locations in the visual field but rather speeds it up most at the slower locations.

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[1] Due to an asymmetry in the monitor luminance, some observers had higher discriminability in the N than S locations, which is reflected in the average data. Once this problem was discovered and corrected, the pattern of discriminability replicated previous findings; i.e., S higher than N. Had this irregularity affected the temporal dynamics, the processing speed in the N would have been slower than reported and thus increased the asymmetry.
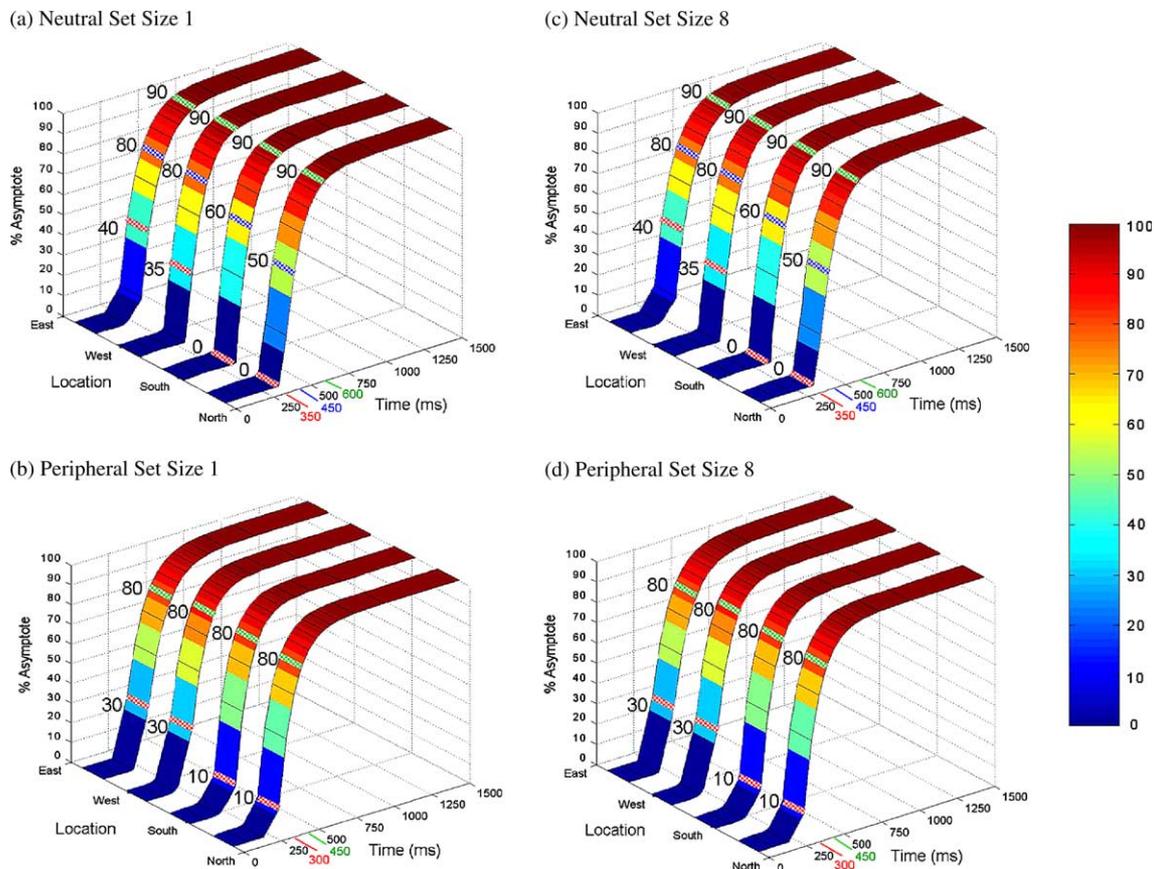
Fig. 7. Speed of visual processing. Differences in processing speed for N, S, E and W locations for set sizes 1 and 8 are illustrated by plotting discrimination normalized by asymptote (λ) as function of processing time. The functions display the time at which each condition reaches a given proportion of its asymptote, using data generated from the parameter estimates of the best-fitting exponential model for the average data. That attention eliminates speed difference is clearly illustrated by the fact that at a given point in time, the colors align across locations much earlier under peripheral cueing conditions than neutral cueing conditions. Additionally, set size graphs are virtually identical ((a) and (b), (c) and (d)), illustrating that set size does not affect the speed of processing at isoeccentric cardinal locations: (a) neutral set size 1; (b) peripheral set size 1; (c) neutral set size 8 and (d) peripheral set size 8.

W locations have each reached 40% and 35% of their asymptotes, respectively, while the N and S location are still at chance level. One hundred milliseconds later (450 ms, indicated by the blue patterned horizontal lines), the temporal asymmetries are still clearly present, with E and W locations reaching 80% of their asymptote, the S location reaching 60%, and the N location reaching only 50%. The temporal asymmetries remain evident for another 150 ms (until 600 ms, indicated by the green patterned horizontal line) when finally all locations reach 90% of their asymptotes.

In the peripheral graphs (Fig. 7b and d), at 300 ms (indicated by the red patterned horizontal lines), 50 ms earlier than in the neutral graphs, E and W locations have reached 30% of their asymptotes and N and S locations have reached only 10%. At 450 ms (indicated by the green patterned horizontal lines), the temporal asymmetries have already disappeared, with all locations at 80% of their asymptotes. The time at which the asymmetries disappear in the precued conditions is approximately 150 ms earlier than the neutral conditions.

5. Discussion

This study has provided the first direct behavioral evidence indicating that the speed of information processing varies as a function of location at a fixed eccentricity, and that directing covert attention to the target location increases the processing speed and attenuates the speed differences among all locations.

Consistent with previous findings of *spatial* performance fields, discriminability was poorer for targets along the vertical meridian than the horizontal meridian (HVA, see also Carrasco & Frieder, 1997; Mackeben, 1999; Rijsdijk et al., 1980; Rovamo & Virsu, 1979), and, along the vertical meridian, discriminability was worst at the N location (VMA). Performance at the intercardinal locations was intermediate between the performance levels at the horizontal and the vertical meridians. Also consistent with past findings, peripheral cueing improved discriminability (e.g., Cameron et al., 2002; Carrasco et al., 2001, 2002; Talgar & Carrasco, 2002) and diminished set size effects at all locations to a similar degree.

Some inconsistencies concerning the existence and the magnitude of the asymmetry between the upper and lower visual fields are present in the literature. However, this may be due largely to the fact that the terms 'VMA' and 'upper-lower visual field differences' have been used inconsistently and in some cases interchangeably. Crucially, a VMA is not equivalent to an overall difference between all of the possible locations in the upper and lower visual fields. It is worth noting that our results do not point to an upper vs. lower hemifield disadvantage. Indeed, performance was similar for targets at the intercardinal locations in the upper and lower visual fields, and the difference between such fields was restricted to the locations on the vertical meridian only. The reported advantage of the lower visual field in a variety of psychophysical tasks (e.g., Edgar & Smith, 1990; Nazir, 1992; Previc, 1990; Rubin et al., 1996) may have been primarily driven by differences along the VM, and should not be generalized to the entire hemifield. Conversely, the lack of a significant difference between the upper and lower visual fields reported in some studies (e.g., Carrasco et al., 1995, 1998; Carrasco & Frieder, 1997) may be due to averaging across several locations, which is likely to have diminished or even obscured a real difference along the VM. As a consequence, we believe that the inconsistencies across reports are due to differences in target location, and that if targets are restricted to the VM, a measurable asymmetry will be evident.

The first novel contribution of this study is in demonstrating *temporal* performance fields, which reflect a temporal analogue of the spatial performance fields. Information accrual was fastest for targets on the horizontal meridian (HVA), intermediate for targets at the intercardinal locations, slow for targets on the vertical meridian, and slowest for targets at the N location (VMA). Accrual time for intercardinal locations was between that for the horizontal and vertical meridians. In short, the pattern of accrual time is: E&W < intercardinal < S < N. For both the neutral and peripheral conditions, set sizes 1 and 8 showed comparable speeds of information accrual. This indicates that set size does not affect the speed with which observers process information at isoeccentric locations and is consistent with other findings suggesting that visual search is mediated by parallel processes in which the speed of processing is unaffected by number of distractors (Carrasco & McElree, 2001; McElree & Carrasco, 1999).

The second novel contribution of this study is that covert attention had a compensatory effect on temporal performance fields, in contrast to its uniform effect on spatial performance fields. Peripheral cueing differentially sped up processing at slower locations, with a greater benefit evident at N than S locations (along the vertical meridian), less of a benefit seen at intercardinal locations, and the least benefit occurring along the horizontal meridian: viz., N > S > intercardinal > E&W. Whereas covert attention does not affect the shape of the spatial performance field, it eliminated the asymmetries in the temporal performance fields by providing most aid to the least privileged locations.

Some models attribute cueing benefits to the reduction of location uncertainty in the display (e.g., Baldassi & Burr, 2000; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Palmer, Verghese, & Pavel, 2000). Although to our knowledge there is no uncertainty model that has directly addressed temporal dynamics, it is reasonable to expect that these types of models would predict that the peripheral cue would speed up information processing more for set size 8 than for set size 1, as there is more uncertainty reduction for the former than the latter. However, consistent with our previous studies (Carrasco & McElree, 2001; Carrasco et al., 2003), adjusted R^2 did not increase when the two set sizes were fit with separate temporal parameters. This result suggests that uncertainty reduction is not responsible for the effect that attention has on the speed of information processing.

We attempted to address whether both the HVA and the VMA would be present, or perhaps even amplified, at a farther eccentricity (9°). However, we were unable to derive stable time-course parameter estimates because the spatial asymmetries became so pronounced at this eccentricity that performance was constrained by floor and ceiling artifacts. Whereas under many circumstances magnified stimuli eliminate discriminability differences (e.g., Carrasco & Frieder, 1997; Kitterle, 1986), we have recently shown that magnified stimuli attenuate, but do not eliminate, differences in temporal dynamics at different eccentricities (Carrasco et al., 2003). In any case, the extent of the observed differences provides a clear and quite remarkable illustration of the magnitude and potential importance of these spatial asymmetries.

5.1. Possible neurophysiological correlates

Although the neurophysiological correlates for the discriminability and temporal dynamics differences at isoeccentric locations are not well established, some anatomical and physiological findings in macaque monkeys suggest possible neural bases for the HVA and VMA.

The HVA may due to a lower density of ganglion cells (Curcio & Allen, 1990; Perry & Cowey, 1985) and a faster decline of cone density with increasing distance from the fovea (Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987) along the vertical as compared to the horizontal meridian of the retina. Evidence of such an HVA also exists in LGN (Connolly & Van Essen, 1984) and V1 (Tootell, Switkes, Silverman, & Hamilton, 1988; Van Essen, Newsome, & Maunsell, 1984).

Possible neural correlates for the VMA include greater cone and ganglion densities in the lower than the

upper visual field (Perry & Cowey, 1985) and a slightly bigger area devoted to the inferior than superior visual field in LGN (Connolly & Van Essen, 1984) and V1 (Tootell et al., 1988; Van Essen et al., 1984). In addition, the projection from V1 to V3/VP and MT arises in layer 4B (Maunsell & Van Essen, 1983), which is closely tied to inputs from the faster magnocellular pathway through the LGN. The map of the visual field on MT is biased to the lower visual field (Maunsell & Van Essen, 1987) and may reflect a higher density of M cells on the corresponding region of the retina. Outputs from layer 4B are thought to provide a signal whose sampling properties match those of M cells (Lennie, 1998). Note, however, that although these differences could be correlates for the VMA, they are not specific to the vertical meridian. Hence, the physiological underpinnings of the VMA are, as yet, unknown.

5.2. Behavioral implications

These performance fields may ultimately derive from the ecological fact that there is typically more relevant visual information across the horizontal than the vertical dimension and at the lower than upper visual fields. Previc (1990), for instance, has proposed that the upper and lower visual fields may be functionally specialized for far and near vision, respectively, so that stimuli are processed more efficiently in the lower than the upper visual field. It is possible that the lower visual field is more important for survival. In primates, for instance, under many viewing conditions, the sky would take up a majority of the superior visual field (Tootell et al., 1988).

The temporal differences across locations without covert attention (~60 ms in the neutral condition) are substantial on the time scale of visual processing. For instance, the human visual system extracts the information necessary to identify a word in the first 50 ms of fixating on a region (Rayner, Inhoff, Morrisan, Slow-iaczek, & Bertera, 1981). Just as strikingly, complex processing of natural scenes is achieved 150 ms after stimulus onset (Rousselet, Fabre-Thorpe, & Thorpe, 2002). Consequently the location-dependent differences in processing time, as well as the location-dependent effect of attention, are likely to have significant perceptual consequences.

For instance, the line motion illusion occurs when a dot appears immediately before an adjacent line, giving the impression that the line is being drawn from the end at which the dot appeared (Shimojo, Miyauchi, & Hikosaka, 1997). Notably, this illusion is most pronounced at locations where we have documented that information accrual is fastest, viz., E&W > S > N. Moreover, in line with present findings that cueing eliminated temporal dynamics asymmetries, peripheral cueing increased the illusion most at the least susceptible locations (N > S > E&W), thereby eliminating the

asymmetries that were otherwise evident in the illusion (Santella & Carrasco, 2003). This study points to but one of the perceptual implications that may follow from the temporal asymmetries documented here.

The existence of HVA and VMA also has several practical implications. With regard to experimental design and analysis, these asymmetries indicate that either the stimuli should be presented in areas of the visual field with similar characteristics, e.g. intercardinal locations, to preclude potential interaction between spatial location and the variable of interest, or performance should be analyzed for different locations separately to specifically evaluate potential interactions. For instance, it has been shown that the contrast psychometric function has higher thresholds and slopes for targets presented in the VM, particularly at the N location, than for targets presented at other locations. The higher threshold reflects the fact that observers require higher contrast in the N location to perform the task at a given level. The steeper slope indicates that observers are more sensitive to a smaller range of contrasts (Cameron et al., 2002).

In the Cameron et al. (2002) study, target location did not interact with other effects of interest (i.e. attention improved discriminability similarly at all locations). However, in studies that have used different locations but constructed performance measures that average across locations, potential visual field asymmetries may be obscured, consequently resulting in the oversight of other effects present at some locations that may not be evident in the average pattern. The need for sampling different locations is illustrated by the current work. Had we used stimuli at the horizontal meridian only, where the effect of covert attention on speed of processing is less pronounced, we might have reached the erroneous conclusion that attention does not accelerate information accrual.

Furthermore, the existence of spatial and temporal performance fields complicate a somewhat standard means of experimentally controlling differences due to other factors like eccentricity. For example, in visual search, target eccentricity has been shown to affect search performance for feature and conjunction searches, and in many cases typical search patterns (i.e., the steepness of the RT × set size function) may be simply a function of target eccentricity (Carrasco et al., 1995, 1998; Carrasco & Frieder, 1997). Somewhat ironically, many (ourselves included) have presented the stimuli at isoeccentric locations to control for sensory factors in visual search (e.g., Cameron et al., 2004; Carrasco & McElree, 2001; Carrasco et al., 2003; Eckstein, 1998; Palmer et al., 2000). The existence of both spatial and temporal performance fields in search tasks, however, indicate that even at a fixed eccentricity, regional variations affect performance and could substantially alter the search pattern.

Finally, another practical implication of the observed field asymmetries concerns ergonomic and human factors applications. The present findings suggest that visual environments for drivers, pilots, and computer operators, among others, can be optimized for speed and accuracy by instrument designs that place critical information at the most sensitive locations in the visual field and that avoid locations, like the upper VM, where information processing will be compromised by its low contrast sensitivity, spatial resolution, and slow temporal dynamics.

To conclude, the location-dependent differences in accrual time as well as in the effects brought about by attention, have significant perceptual consequences, and will need to be addressed by comprehensive neurophysiological, computational, and cognitive theories of visual processing.

Acknowledgements

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