

DISCRIMINATION WITHIN AND BETWEEN HEMIFIELDS: A NEW CONSTRAINT ON THEORIES OF ATTENTION

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Abstract—Subjects were presented with two groups of characters and were to decide whether they were the same or different. The stimulus groups differed either by a single feature (“preattentive” trials) or by a conjunction of features (“attentive” trials). The two stimulus groups appeared at the corners of an imaginary square centered about the fixation point, falling either in the same or different hemifields. In two experiments, subjects evaluated both types of stimuli faster when they were presented in different hemifields than in the same hemifield. Subjects also compared pairs of single characters faster when they appeared in different hemifields. Finally, this different-hemifield advantage was eliminated when the characters appeared sequentially. These results indicated that two stimuli that appear simultaneously in the same hemifield engender either a competition for common processing structures or intrahemispheric inhibition.

INTRODUCTION

ATTENTION often serves to select information at a particular location for further processing. Although the fact that attention can be allocated to different regions of space is well-established, the mechanisms responsible for this process are still unclear. The present article reports experiments designed to distinguish among theories of the spatial structure of attention. These theories were devised to account for results from experiments that reflect the spatial properties of attention. For example, subjects require less time to detect targets at expected locations compared to unexpected locations throughout the visual field. There are three general classes of theories designed to account for such results.

First, perhaps the oldest theories of the spatial structure of attention posit that subjects require more time to encode targets at unexpected locations because they must shift an “attentional spotlight.” These *shifting focus theories* maintain that attention is shifted in an analog fashion, operating like a spatially restricted “beam” ([27, 32, 40]; see [9, 45] for recent critical reviews). Second, some recent theories posit no movement of attention *per se*. *Gradient theories* explain the effect of expectancy by a mechanism that allocates “processing resources” to particular locations; the farther a stimulus is from the locus of attention, the less processing resources are available. The shape of this attention allocation gradient is determined by initial task demands (e.g. information about where to expect the target) as well as the distribution of target probabilities across locations. Third, *hemifield theories* also posit a gradient of attention, but this gradient is relatively flat and extends throughout the visual

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hemifield in which the target is expected, resulting in a modest benefit in that hemifield together with a more robust inhibition in the opposite hemifield. HUGHES and ZIMBA [14] note that the two possible stimulus locations used by Posner and his colleagues always crossed the midline, producing the appearance of increased time with distance. HUGHES and ZIMBA [15] further assert that reports of graded changes in attention within a hemifield [7, 33, 34] in fact reflect the presence of non-target stimuli that are used to cue locations where targets can appear with the visual field. They claim that the putative gradient is an artifact, caused by masking induced by the cues.

The picture is further complicated by recent reports that there are costs to shifting attention not only across the vertical meridian, but also across the horizontal meridian [15, 28]. However, HUGHES and ZIMBA [15] report that subjects have larger decrements in performance when their attention crosses the vertical meridian than when it crosses the horizontal meridian. Hughes and Zimba originally postulated that the effect of shifting attention across the vertical meridian resulted from shifting processing from one cerebral hemisphere to the other, across the corpus callosum. The more recent evidence showing an effect across the horizontal meridian clouds this picture; the horizontal meridian is not an interhemispheric barrier. However, it is known that in extrastriate cortex, upper and lower visual field representations of cortical areas are often separated and are not always spatially contiguous [42]. Although the horizontal meridian does not correspond to the interhemispheric barrier, it may correspond to an intrahemispheric barrier. Thus, "hemifield theories" may be based on too simple a conception of the brain's division of the visual world into regions.

LABERGE [18] and LABERGE and BROWN [191] report results that challenge both shifting focus and gradient theories. They found that subjects could detect targets faster if they attended to a relatively large area than if they attended to a relatively small area. According to a continuous shifting focus theory of attention (with a constant shift velocity), people should require more time to shift attention over larger distances; according to a gradient theory with fixed capacity, people should take longer when attending to a larger area because fewer processing resources should be available at each location within that range. The attentional range effect saddles both theories with burdensome modifications, such as *ad hoc* assumptions about changing shifting rates or variable amounts of capacity.

The challenge of formulating a theory of attention is even more daunting when we consider the growing body of neurophysiological findings. For example, cells in posterior parietal cortex show enhanced responses when an animal pays attention to stimuli that fall within these cells' receptive fields [43, 44]. In another study, MORAN and DESIMONE [21] reported selective attention for locations within the receptive fields of cells in V4 and IT cortex. In this case, when an animal had been trained to attend to a region of space that was a portion of a cell's receptive field, the neuron was inhibited from firing when the stimulus fell in the unattended region—even though it was within the cell's receptive field.

Attention is reflected not only by modulation of the spatial selectivity of neurons, but also by their stimulus selectivity. For example, in many visual areas of the cortex, stimuli presented outside the "classical receptive field" (CRF) of a cell strongly and selectively influence the neural response of the cell to stimuli presented within the CRF. For instance, in area MT (where cells are directionally selective) the responses of many cells are facilitated by background movement in the direction opposite to that preferred within the CRF [1]. Other researchers have reported separate populations of neurons that are sensitive to differences in a single feature dimension (see [6, 46 47], for cells sensitive to differences in orientation,

spatial frequency and color). This sort of modulation may function as a mechanism of "preattentive" detection as defined by TREISMAN and GELADE [37] and JULESZ and BERGEN [16].

One difficulty in interpreting these empirical results stems from important differences among the paradigms used in the studies. Three differences seem most pertinent. First, in many experiments the stimuli were spots of light [15, 24, 25, 27, 32, 40, 43, 44], whereas in others they were more complex (e.g. letters, words and colored oriented bars; [10, 18, 19, 21]). The detection of spots of light can be accomplished by a parallel (preattentive) process, whereas detection of complex stimuli (i.e. a particular conjunction as opposed to other possible combinations) requires a serial (attentive) process [16, 23, 37].

Second, the various experiments used different tasks. The experiments in which the stimuli were dots or points of light employed detection tasks, whereas the experiments of ERIKSEN and YEH [10], LABERGE [18] and LABERGE and BROWN [19] employed identification tasks. These differences in the tasks cannot help but engender differences in processing.

Finally, all of the experiments discussed required selective attention to particular locations, but the experiments by ERIKSEN and YEH [10], LABERGE [18] and LABERGE and BROWN [19] also required selective attention to particular stimulus features. Although spatial selection was manipulated in these experiments, the task itself was to categorize or discriminate between sets of characters or sets of strings of characters; hence, the subjects had to attend to specific stimulus features.

In order to resolve the disparate conclusions reached by various investigators, we must consider what types of processing are required in the different tasks. It seems possible that attention might operate in different ways at different levels of processing. Specifically, processing is often divided into two general levels: "early" processing detects single-feature differences preattentively; at this level, attention may reflect gradients of processing in topographically mapped areas of visual cortex, which are critical in the initial processing of the input (primarily divided by hemifield, as seen in HUGHES and ZIMBA [14, 15] and WURTZ *et al.* [43, 44], but also divided by quadrant, as seen in HUGHES and ZIMBA [15]). In contrast, "later" processing is required to discriminate stimuli; at this level, attention may operate as a variable-sized spotlight (as seen in [16, 18, 19, 37]).

Experiment 1 was designed to investigate whether attention operates differently at different levels of processing, and whether one theory may be most appropriate for low-level processing and another for higher-level processing.

EXPERIMENT 1

The task used here requires subjects to discriminate between two stimulus groups, which are always separated by approximately equal distances; thus, we keep constant the primary factor that should affect a shifting focus mechanism, and can thereby evaluate the hemifield theory independently of the shifting focus theory. The two stimulus groups are presented either vertically, within a visual field, or horizontally, straddling the midline. Furthermore, on some trials, the stimuli consist of patterns that can be discriminated preattentively, whereas on other trials they consist of patterns that can be discriminated only by using focal attention.

Thus, we will examine the distribution of attention across the same hemifield and across different hemifields when subjects can use "preattentive" processing or are required to use

"attentive" processing. For trials that can be performed using preattentive processing, we expect subjects to be faster and more accurate when stimuli fall within the same hemifield. In this case, there should be inhibition (similar to that shown by HUGHES and ZIMBA [14, 15]) when stimuli are in different fields, impeding processing.

In contrast, for trials requiring attentive processing, we have two alternative hypotheses. First, attention may be a function of distance. If attention is solely a function of distance, as predicted by shifting focus theories, then approximately equal amounts of time should be required to evaluate stimuli in the same field and in different fields; the stimuli are separated by about the same distances in the two conditions, and hence roughly equal amounts of time should be required to shift attention between them. This hypothesis is based on the assumption that focal attention is required to discriminate the characters in each stimulus group, much like what is believed to occur when subjects evaluate conjunctive displays [3, 37]. In these experiments focal attention is shifted serially from one position to another in approximately 50–60 msec steps.

Alternatively, the data that implicate attentional shifting in part may be an artifact of whether stimuli fall in one or two visual fields. If so, then—as suggested by Hughes and Zimba—we expect subjects to be faster and more accurate when these stimuli fall within the same hemifield.

Method

Subjects. Eight male and eight female students (undergraduate, graduate and one post-doctoral fellow), between the 18 and 31 years of age, volunteered to serve as paid subjects. In this and all following experiments, all subjects were right-handed, had normal or corrected-to-normal visual acuity, and were ignorant of the purposes and predictions of the experiment at the time of testing.

Stimuli. The stimulus groups appeared in two of four possible locations, which corresponded to the vertices of a square centered about a fixation point. Vertices along the diagonals were used in the "different hemifield" condition whereas vertices on the left and right sides were used in the "same hemifield" condition. Each stimulus group was composed of a single character, replicated in eight nearby locations. Groups of the same character were used instead of single characters because the targets used in typical visual search tasks are embedded in a set of distractors. Three characters were used, each composed of identical physical features, a horizontal and a vertical line of equal length. Characters were chosen such that some could be discriminated preattentively whereas others required focal attention. Two of the characters ("T" and "L") differ only in the conjunction of their features and thus require focal attention in search and texture segregation tasks [2, 16, 38, 39]. Although the third character ("+") is also a conjunction of the same two features, its combination of features generates a new property (the crossing of line segments), which functions as an emergent feature [26, 38]. Emergent features, such as crossing segments, can be processed preattentively (e.g. as shown by the fact that they "pop-out" in search; see [16]).

Thus, trials on which subjects had to discriminate between "T" or "L" stimulus displays should require focal attention, whereas trials on which they had to discriminate at least one "+" stimulus display should be able to be evaluated preattentively. The visual displays appeared on a Macintosh Plus screen.

The four possible locations (centered about the fixation point) were at the vertices of a square that measured 8.51 cm \times 8.51 cm, which at a viewing distance of 38.1 cm (the distance of the Macintosh screen from the chin rest) subtended 12.5° \times 12.5°. Only four of the six possible pairs of locations were used: two combinations with both stimulus groups in the same hemifield (both on the left or both on the right) and two combinations with stimulus groups in opposite hemifields (the two diagonals). The centers of stimulus groups in the same hemifield were separated by 5.64 cm (8.4°); the centers of stimulus groups located in opposite hemifields were separated by 8.26 cm (12.2°). Stimuli appeared in each pair of locations equally often.

Each stimulus group was 2.79 cm \times 2.79 cm (subtending 4.2° \times 4.2°), and was patterned after a square array with 16 possible positions. Each group was always composed of a single character type, as illustrated in Fig. 1. A character was randomly assigned to half the positions (i.e. eight) within the group. Two such random patterns were generated. The same two random patterns were used for each of the three characters, thereby generating six stimulus groups (i.e. two stimulus groups for each character; see Fig. 1). Because there was more than one stimulus display for each character type, on some trials two different fields of the same character were displayed. Because both fields were composed of the same characters, the correct response should have been "same." This feature of the design was included so that subjects would compare the individual characters in the two stimulus groups and not their overall global patterns. Each character appeared eight times and in four different orientations (up, down, left and right—two replication of each) within a group.

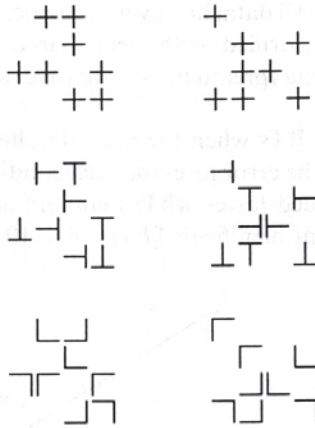


Fig. 1. The six stimulus groups that appeared in Experiments 1, 2 and 3.

Procedure

The subjects first were asked to complete an informed-consent form, and then were given a brief introduction to the equipment, including a demonstration of the operation of the mouse and response keys. Following this, they read the instructions and were shown sample stimulus groups that illustrated the different types of trials. They were told that the task was to decide whether stimulus groups were composed of the same or different characters, regardless of their overall pattern, and that the groups would appear for only a brief period of time. The subjects were asked to respond as quickly as possible without sacrificing accuracy. None of the sample stimulus groups were included as test trials. The subjects were then asked to paraphrase the instructions and were specifically warned about trials in which stimulus displays had different patterns but were composed of the same characters.

Each trial consisted of four events: (a) a fixation point (a small cross) appeared in the center of the screen; after fixating, the subject pressed the button on the mouse; (b) 200 msec after the subject pressed the button, two groups of stimuli appeared along with the fixation point for 180 msec; (c) the stimulus groups were replaced by a blank screen; and (d) when the subject pressed either of two keys, "s" (same) or "d" (different), the fixation point reappeared and a new trial began. The stimulus screen remained visible for only 180 msec in order to prevent saccadic eye movements. The subjects rested their heads on a chin support throughout to minimize head movements and to maintain a constant viewing distance.

All subjects responded with their right index fingers. At the beginning of each trial, this finger rested on a neutral key between the two labeled response keys. The subjects were told to press "s" if the stimulus groups contained the same characters and "d" if the stimulus groups contained different characters. For half the subjects (balanced across gender) the "s" response key was to the left and the "d" response key to the right. For the other half, this order was reversed. The mouse was controlled by the non-dominant (left) hand.

The subjects evaluated four blocks of 32 practice trials, which were balanced for all conditions (hemifield, position within hemifield, preattentive-attentive processing and response). During the practice trials, the subjects received immediate feedback (a beep) whenever they made an error, and were told how many errors they made after each practice block. This procedure enabled subjects to reach acceptable accuracy rates (75% or higher) and to stabilize their response times. After the experimenter answered any questions about the procedure, the subjects were allowed to complete the experiment.

The actual experiment included 128 trials. There were five regularly spaced brief breaks in the experiment as the computer loaded more trials. Furthermore, the subjects were instructed to pause if need be during the initial fixation point screen until she/he was ready for the next trial. The apparatus was located in an isolated room and the experiment was conducted under dim illumination; the subjects could not see the experimenter during testing.

Results and discussion

There were eight observations per cell (i.e. trial type) for each subject. In this and all following experiments, response times (RTs) more than 2.5 times the mean of the remaining observations in each cell were treated as outliers, and hence were eliminated prior to data analysis. In this experiment, this procedure removed 1.5% of the data. Response times from incorrect responses were also eliminated prior to data analysis, which in this experiment led

us to discard 19.0% of the data. All data, however, were included in the analysis of accuracy. Analyses of variance were performed with field (same, different), location (left/right, top/bottom), necessary processing (preattentive, attentive) and response (same, different) as independent variables.

Figure 2 illustrates the mean RTs when the two stimulus groups appeared either in the same or in different hemifields; the error rates for each condition are provided in Table 1. As is evident, the subjects responded faster while maintaining the same accuracy when the stimulus groups were in different hemifields [$F(1, 14) = 10.33, P < 0.01$]. This pattern was

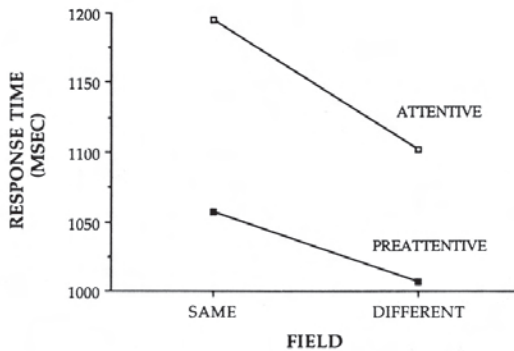


Fig. 2. Mean response times in Experiment 1 when the two stimulus groups appeared in the same or different hemifields for stimuli that can be evaluated preattentively and for stimuli that require attentive processing.

Table 1. Per cent error for Experiments 1, 2 and 4 for two types of processing when stimuli occurred in the same or different visual field

Experiment	Processing × Field			
	Preattentive		Attentive	
	Same	Different	Same	Different
1	9.6	7.2	30.7	28.7
2	5.1	6.4	22.3	21.3
4	8.8	5.6	15.5	9.6

obtained both for trials on which stimuli could be discriminated preattentively and for trials on which stimuli could be discriminated only using focal attention [$F(1, 14) = 1.62, P > 0.2$] for the interaction of field and stimulus type. These results conflict with all three of the theories reviewed earlier. None of the theories of attention (shifting focus, gradient or hemifield) predicts faster RTs when stimulus groups appear in different hemifields compared to when they appear in the same hemifield.

Figure 2 also illustrates that, as expected, the subjects required more time to evaluate stimulus groups that required attentive processing [$F(1, 14) = 5.39, P < 0.05$]. That is, trials in which one of the stimulus groups included the "+" character could be evaluated preattentively, and thus engendered shorter RTs than trials that required focal attention for discrimination.

We also found, however, an unexpected interaction with the type of necessary processing.

The subjects evaluated same stimulus groups at about the same speed, regardless of whether the stimulus groups could be evaluated preattentively (1050 msec) or required attentive processing (1070 msec); in contrast, they evaluated different stimulus groups faster if they could be evaluated preattentively (1015 msec) than if they required attentive processing (1228 msec), as witnessed by an interaction between processing and response [$F(1, 14) = 13.51, P < 0.003$]. In some circumstances, then, preattentive processing apparently can detect a difference more easily than an identity.

Two other results were marginally significant. The subjects tended to respond "same" faster than "different" (61 msec) [$F(1, 14) = 3.07, P = 0.10$]. In addition, the subjects tended to evaluate stimulus groups that were the same faster when they were in opposite fields (1000 msec) than when they were in the same field (1120 msec), whereas they tended to evaluate stimulus groups that were only slightly faster when they were in opposite fields (1109 msec) than when they were in the same field (1133 msec) [$F(1, 14) = 4.10, P < 0.10$].

In this and all following experiments, we also analyzed the data including RTs from trials on which incorrect responses were made. In all experiments except the present one, the primary significant results from the main analysis were preserved when all the data were considered, $P < 0.05$ in all cases; in the analysis of data from Experiment 1, the different-hemifield advantage just missed the conventional level of significance ($P < 0.06$). Thus, removing the times from incorrect trials did not alter the picture painted by the analysis of times to make correct responses.

Finally, the accuracy rates were analyzed the same way as the response times. There were no speed-accuracy tradeoffs for the significant or marginally significant effects found in the response time analyses. Subjects evaluated stimuli that required attentive processing less accurately than stimuli that could be evaluated using preattentive processing [$F(1, 14) = 140.72, P < 0.0001$]. In addition, when attentive processing was required, the subjects' accuracy decreased by only 11.3% on same trials, compared to 31.2% on different trials [$F(1, 14) = 7.32, P < 0.02$] for the interaction between processing and response. There was also an interaction between gender, type of processing and location of stimulus groups nested within the hemifield condition [$F(2, 28) = 4.56, P < 0.02$], which was difficult to interpret. No other effects or interactions approached significance ($P > = 0.10$ in all cases).

EXPERIMENT 2

The results of Experiment 1 were unexpected; they were not predicted by any of the theories being considered. The present experiment had three purposes: First, the different-field presentation advantage found in Experiment 1 was so surprising that we wanted to replicate it. Second, on reflection, it seemed possible that facilitation might occur in the different-hemifield condition because of the diagonal locations of the stimulus groups, which involved shifting attention across the fixation point. In this experiment we eliminated this requirement. Finally, it seemed wise to control more precisely for distance between the two stimuli in the same- and different-hemifield conditions.

Thus, in Experiment 2 we repeated Experiment 1 but changed the locations of stimuli in the different-hemifield condition. Specifically, the two top or two bottom corners of the square were used in the different-hemifield condition instead of the diagonal positions (which not only crossed the fixation point, but were separated by a slightly greater distance). The same subjects were retested to discover whether the advantage for the different-hemifield condition would persist after modifying the location of stimulus groups.

Method

Subjects. The same 16 subjects tested in Experiment 1 were tested in this experiment. All subjects were tested 1–2 weeks after the first experiment and remained naive about the aim of the study at the time of testing.

Stimuli. The conditions in Experiment 2 were exactly the same as those of Experiment 1 except that we changed the locations of the different-field stimuli. Now the stimulus groups appeared either at the top two corners of the square or at the bottom two corners. Thus, in this experiment we perfectly equated the distance between stimulus groups in the same- and different-hemifield conditions (5.64 cm, 8.4°).

Procedure. The procedure was identical to that of Experiment 1. All subjects were tested under the same response conditions under which they were originally tested in Experiment 1. That is, if for a particular subject the key labelled "s" was to the left and the key labelled "d" was to the right in Experiment 1, then the same arrangement prevailed for that subject in Experiment 2.

Results and discussion

The data were analyzed as in Experiment 1. The elimination of outliers removed 0.6% of the data. As before, RTs from incorrect responses were also eliminated prior to data analysis, which removed 13.3% of the data.

Figure 3 illustrates the mean RTs when the two stimulus groups appeared in the same or in different hemifields; the error rates for each condition are provided in Table 1. As in Experiment 1, the subjects responded faster when the stimuli were in different hemifields [$F(1, 14) = 20.54, P = 0.0005$]. As before, this effect was comparable for trials on which stimuli could be evaluated preattentively and for trials on which stimuli had to be evaluated using focal attention ($F < 1$ for the interaction of type of processing and field). Again, this result conflicts with all theories reviewed.

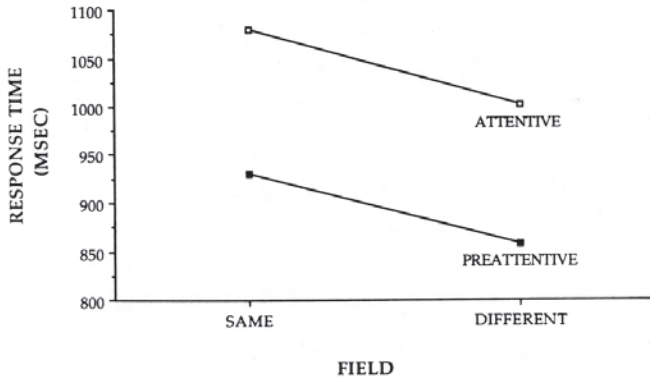


Fig. 3. Mean response times in Experiment 2 when the two stimulus groups appeared in the same or different hemifields for stimuli that can be evaluated preattentively and for stimuli that require attentive processing.

Figure 3 also illustrates the mean RTs when the two stimulus groups could be evaluated preattentively or required attentive processing. As in Experiment 1, subjects were slower to evaluate stimulus groups that required attentive processing [$F(1, 14) = 45.76, P < 0.0001$]. In addition, subjects responded 76 msec faster for same trials [$F(1, 14) = 13.85, P < 0.003$]. Only one interaction was significant in the first experiment but not in the present experiment: subjects no longer responded faster and more accurately for different judgements on preattentive trials and slower and less accurate for different judgements on attentive trials, as witnessed by a non-significant interaction between type of necessary processing and response

[$F(1, 14) = 2.25, P > 0.15$]. On both preattentive and attentive trials, the subjects were faster and more accurate for same judgements than different judgements.

Two interactions were significant in the present experiment but not in Experiment 1. The subjects responded "different" 76 msec faster when stimuli appeared in the left visual field as opposed to the right, but responded "same" 29 msec slower when stimuli appeared in the left visual field (cf. [8]); in addition, subjects responded "same" 14 msec faster when stimuli appeared in the top corners as opposed to the bottom corners and responded "different" 18 msec slower when stimuli appeared in the top corners [$F(2, 28) = 7.65, P < 0.0025$ for the interaction between location within hemifield and response]. In addition, there was an interaction involving location within hemifield by response and gender [$F(2, 28) = 4.65, P < 0.02$], which was difficult to interpret. All other effects and interactions were not significant ($P > 0.10$).

Finally, the error rates in Experiment 2 were analyzed the same way as the response times. The mean error rates are presented in Table 1. Again, this analysis revealed no speed-accuracy tradeoffs for the significant effects found in the response time analysis. Subjects evaluated stimulus groups that required attentive processing less accurately than stimulus groups that could be evaluated using preattentive processing [$F(1, 14) = 46.08, P < 0.001$]. In addition, males had more errors on preattentive trials when the stimuli appeared in different fields (a difference of 2.4%) and fewer errors on attentive trials when the stimuli appeared in different fields (a difference of 3.5%), unlike females who had slightly more errors on both preattentive and attentive trials when the stimuli appeared in different fields (a difference of 0.4% and 1.6%, respectively). This pattern of results was witnessed by an interaction between field, processing and gender [$F(1, 14) = 5.00, P < 0.05$]. Two higher order trends towards interactions were difficult to describe or interpret: field by type of necessary processing by response [$F(1, 14) = 3.42, P < 0.10$], and gender by field by type of necessary processing by response [$F(1, 14) = 3.92, P < 0.10$]. All other effects and interactions were not significant ($P > 0.10$).

EXPERIMENT 3

Experiments 1 and 2 demonstrate that subjects evaluate groups of stimuli faster when they appear in different hemifields. The most straightforward way to interpret this finding is that each hemisphere can perform some aspect or aspects of the task independently. If so, then the subjects respond faster when stimuli appear in different fields either because the hemispheres have separate "resource pools", or because there is less interference between processes in the different hemispheres than between processes within a single hemisphere.

In either case, the different-field advantage should only arise because the cerebral hemispheres operate in parallel. If so, we reasoned, then this advantage should be eliminated if the stimuli are presented sequentially. Presenting the stimulus groups one at a time should reduce early parallel processing when stimuli are presented in different hemifields (thereby slowing responses on these trials), and should reduce competition for resources when they are presented in the same hemifield (thereby facilitating responses on these trials). Thus, in Experiment 3 we replicated Experiment 2 with one change; the stimulus groups were presented sequentially.

Method

Subjects. Twelve male and 12 female students volunteered to serve as paid subjects. None of these subjects had participated in Experiments 1 or 2.

Stimuli. This experiment used the materials of Experiment 2. However, every pair of stimulus groups now appeared twice, with the order of presentation reversed in the two versions. For example, if the two appeared at the top of the screen, on one trial the one at the left appeared first and then the one at the right, and vice versa on the other trial.

Procedure

The procedure was identical to that of Experiments 1 and 2 except that the two stimulus groups on a given trial were presented sequentially. Each display was visible for 167 msec, with a minimal delay between them (i.e. with a maximum of 16.67 msec, required to refresh the entire computer screen). Thus, each trial consisted of the following four events: (a) a fixation point appeared; when the subject was fixated, he or she pressed the button on the mouse; (b) 200 msec later, one stimulus group appeared for 167 msec, directly followed by a second stimulus group, which also appeared for 167 msec; (c) a blank screen then appeared and (d) when the subject pressed either response key, this blank screen was replaced by a fixation point. Each stimulus screen was presented for only 167 msec in order to prevent saccadic eye movements.

The response conditions were changed slightly in this experiment. Half of the subjects (balanced across gender) responded with their right hands and initiated trials by pressing the button on the mouse with their left hands, the other half responded with their left hands and pressed the button on the mouse with their right hands. The index and middle finger of the response hand rested on adjacent response keys. For half the subjects (balanced across gender and hand of response) the "s" response key was to the left and the "d" response key to the right, and vice versa for the other half.

This experiment included four blocks of 32 practice trials, which were balanced for all conditions (field, location within field, direction of movement, type of necessary processing and response). The actual experiment included 256 trials.

Results and discussion

The data were analyzed as in the previous experiments; 0.4% of the data were discarded as outliers and RTs from an average of 15.6% of incorrect responses were also eliminated prior to data analysis. An analysis of variance was performed on the data which included field (same and different hemifields), location nested within field (same hemifield: left and right visual fields; and different hemifields: top and bottom), direction of movement nested within field (same hemifield: left and right; and different hemifields: up and down), type of necessary processing (preattentive or attentive), and response (same and different) as factors.

In striking contrast to the results from Experiments 1 and 2, the subjects required the same amount of time to evaluate stimulus patterns in the same (1043 msec) and different hemifields (1052 msec) [$F(1, 23)=1.27, P>0.25$]. This finding suggests that the different-field advantage we found before may be due to early parallel processing in the two hemispheres or a reduction in intrahemispheric competition for resources.

As expected, the subjects compared stimuli that could be discriminated preattentively (959 msec) faster than stimuli that required attention (1136 msec) [$F(1, 23)=49.9, P<0.0001$]. The subjects also evaluated same stimuli (1003 msec) faster than different ones (1092 msec) [$F(1, 23)=14.7, P<0.001$]. However, when stimulus groups could be evaluated preattentively, the subjects evaluated same groups only 54 msec faster than different ones, but when attention was necessary, they evaluated same displays 124 msec faster than different ones; this divergence was reflected by a marginally significant interaction between necessary processing and response [$F(1, 23)=3.4, P<0.08$]. Two other higher-order interactions involving four and five factors were marginally significant but difficult to interpret: location and direction (nested within field) and type of necessary processing; and, location and direction (nested within field), type of necessary processing, and response [$F(2, 46)=2.8, P<0.07$; and $F(2, 46)=2.7, P<0.08$, respectively]. All other effects and interactions were not significant ($P>0.10$).

Finally, the error rates were analyzed the same way as the response times. This analysis revealed no speed-accuracy trade-offs for the significant effects found in the correct response

time analysis. Mirroring the RT analyses, the subjects evaluated stimulus groups in the same hemifield (16.1%) as easily as those in different hemifields (16.0%) ($F < 1$). Subjects made 17.8% more errors for stimuli that require attention (24.9%) than for those that can be evaluated preattentively (7.1%) [$F(1, 23) = 203.1, P < 0.0001$]. In addition, the subjects made fewer errors when stimuli were in the top (14.1%) than bottom positions (17.8%), but made equivalent errors when stimuli were in the left (15.9%) and the right (16.3%) visual fields, as witnessed by a significant effect for location nested within field [$F(2, 46) = 4.2, P < 0.025$]. The subjects were equally accurate for same and different groups of stimuli that did not require focal attention (1.1% difference), but tended to make more errors (6.4% difference) for different as opposed to same groups of stimuli that did require focal attention, as witnessed by a marginally significant interaction between the type of necessary processing and response [$F(1, 23) = 4.2, P < 0.06$].

Two other higher-order interactions were marginally significant: direction nested within field and response [$F(2, 46) = 2.8, P < 0.08$], and location and direction nested within field and type of necessary processing [$F(2, 46) = 3.1, P < 0.06$]. All other effects and interactions were not significant ($P > 0.10$).

Thus, the results from Experiments 1, 2 and 3 suggest that the cerebral hemispheres can perform at least part of the matching task in parallel; there is a different-hemifield advantage when the stimuli are presented simultaneously, and hence the two groups are processed at the same time, but there is no such advantage when the stimuli are presented sequentially, and hence they do not compete for resources. The results from these experiments, then, suggest that there exist hemisphere-specific mechanisms or structures that are used in this task. Experiment 4 investigates one hypothesis about the nature of the independent resources.

EXPERIMENT 4

We have evidence that the hemispheres independently can perform at least some of the processing used to compare groups of stimuli. One process that might benefit from such a division of labor is figure/ground segregation. Before the stimuli can be compared, a single character must be segregated from each group; perhaps this requirement makes the discrimination relatively difficult, and so it is useful to process each stimulus separately in the different hemispheres. It seems reasonable that low-level processing in the two hemispheres operates independently to isolate individual objects in the field. In Experiment 4 we test this hypothesis. We reasoned that if the different-hemifield advantage arises because figure/ground segregation is performed in parallel in the two hemispheres, then this advantage should be greatly reduced if only a single character appears in each group. Parsing a single character from a blank field is much easier than parsing figures of various orientations in the stimulus groups used previously.

Method

Subjects. Sixteen (eight male and eight female) Harvard University undergraduate and graduate students volunteered to participate as paid subjects. None of these subjects had participated in the other experiments reported in this article.

Stimuli. The stimuli were the same three characters (+, T, L) used in Experiments 1, 2 and 3 except that they were presented in isolation. T and L were oriented 90°, 180° or 270° from their standard upright positions. On each trial, two characters were presented at two of the vertices of an imaginary square centered about the fixation point. The combinations of locations used in Experiment 2 were also used here (same hemifield: both on the left or both on the right, and different hemifield: the top or bottom corners of the square). The characters were always 5.5 cm apart, subtending 8.4° at a viewing distance of 38.1 cm. Each character measured 0.5 cm × 0.5 cm (subtending 0.75° × 0.75°). In all other respects, the stimulus conditions were like those used in Experiment 2.

Procedure

The procedure was identical to that of Experiment 3, except that stimuli appeared simultaneously. The subject's task was to decide on each trial whether the two characters that appeared on the screen were the same or different, regardless of orientation. There were 32 practice trials, which were balanced for all conditions (field, location within field, type of necessary processing, and response). The actual experiment included 192 trials.

Results and discussion

There were 12 observations per cell (i.e. trial type) for each subject. The trimming procedure eliminated 0.65% of the data, and 9.9% of the data were eliminated when we discarded RTs from incorrect responses. We performed an analysis of variance that included field (same and different hemifields), location nested within field (same hemifield: left/right visual hemifield; and different hemifields: top/bottom), necessary processing (preattentive or attentive), and response (same and different) as factors.

As is evident in Fig. 4, the subjects compared stimuli faster (52 msec) when they appeared in different hemifields [$F(1, 15) = 10.82, P < 0.005$]; the error rates for each condition are provided in Table 1. This result was obtained both for trials on which stimuli could be discriminated preattentively and for trials on which stimuli could be discriminated only using focal attention ($F < 1$ for the interaction of field with necessary processing). Thus, our hypothesis is ruled out; the different-hemifield advantage does not arise from the independent use of both hemispheres to segregate a single character from a group. Figure/ground segregation does not seem to be the rate-limiting step. Instead, each hemisphere apparently can independently perform higher-level encoding.

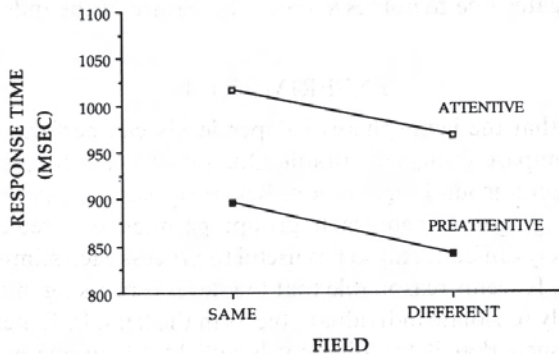


Fig. 4. Mean response times in Experiment 4 when the two stimuli appeared in the same or different hemifields for stimuli that can be evaluated preattentively and for stimuli that require attentive processing.

In addition, we also found that the different-hemifield advantage was larger for same stimuli: the subjects evaluated same stimuli 87 msec faster when they were presented in different hemifields (843 msec) than in the same hemifield (930 msec), whereas they evaluated different stimuli only 17 msec faster when they were presented in different hemifields (965 msec) than within the same hemifield (982 msec); this difference was witnessed by an interaction between field and response [$F(1, 15) = 5.27, P < 0.04$].

Figure 4 also illustrates that the subjects required more time (123 msec) to evaluate characters that require focal attention than those that can be evaluated preattentively [$F(1, 15) = 43.26, P < 0.0001$]. However, this difference was only 78 msec for different

stimuli, whereas it was 168 msec for the same stimuli, as witnessed by an interaction between necessary processing and response [$F(1, 15) = 5.42, P < 0.035$]. The subjects also evaluated same trials faster (87 msec) than different trials [$F(1, 15) = 26.05, P < 0.0002$]. We also found a higher order interaction between the type of necessary processing and location of stimuli nested within the hemifield condition [$F(2, 30) = 6.26, P < 0.006$], which was difficult to interpret. For all other effects and interactions, $P > 0.10$.

Finally, we analyzed error rates the same way as the response times. The subjects made fewer errors when the stimuli straddled the fields (7.6%) than when they were within a single hemifield (12.2%) [$F(1, 15) = 18.65, P < 0.0007$]. In addition, they made fewer errors when stimuli could be evaluated preattentively [$F(1, 15) = 8.22, P < 0.012$]. However, the subjects made more errors when judging same stimuli [$F(1, 15) = 6.92, P < 0.02$], thereby exhibiting a speed-accuracy tradeoff for this variable. In addition, the subjects evaluated different stimuli with only 1.9% fewer errors when they were presented in different hemifields (6.0%) than in the same hemifield (7.9%); in contrast, they evaluated same stimuli with 7.2% fewer errors when they were presented in different fields (9.2%) than in the same hemifield (16.4%), as witnessed by an interaction between field and response [$F(1, 15) = 6.37, P < 0.025$]. Furthermore, for different stimuli, the subjects evaluated stimuli when preattentive processing could be used with only 0.9% fewer errors than when attention was necessary; in contrast, for same stimuli, they evaluated stimuli when preattentive processing could be used with 9.8% fewer errors than when attention was necessary, as witnessed by an interaction between the type of necessary processing and response [$F(1, 15) = 6.74, P < 0.025$].

Finally, only one interaction between field and the type of necessary processing was marginally significant in this analysis. When stimuli could be encoded using preattentive processing, the subjects made 3.2% fewer errors when stimuli were presented in different hemifields (5.6%) than in the same hemifield (8.8%); in contrast, when attention was necessary, they made 5.9% fewer errors when stimuli were presented in different hemifields (9.6%) than in the same hemifield (15.5%), as reflected by a marginal interaction between field and type of necessary processing [$F(1, 15) = 3.97, P < 0.07$]. For all other effects and interactions, $P > 0.10$.

GENERAL DISCUSSION

Contrary to shifting focus, gradient and hemifield theories, subjects evaluated two stimuli faster when they appeared in different hemifields. This different-hemifield advantage was present when the stimulus groups were both on the top or both on the bottom, straddling the midline, or when they appeared on opposite ends of a diagonal. This different-hemifield advantage was also present when only a single stimulus character was presented in each hemifield; thus, the advantage accrues from rather high-level processing, not simply figure/ground segregation. We eliminated the effect, however, when the stimuli were presented sequentially. This finding was impressive because each stimulus was visible for only 167 msec, and there was the briefest possible delay between them (the time to refresh the computer screen).

In order to present the stimulus groups in different hemifields, we necessarily had to arrange the stimuli horizontally; to present the stimulus groups in the same hemifield, we arranged them vertically. Thus, one could argue that the different-hemifield advantage occurs because of the display configuration; perhaps the subjects could discriminate the stimuli faster because they were arranged horizontally *per se*, rather than vertically. If so,

however, then we should have found a similar result in Experiment 3, when the stimuli were presented sequentially. In addition, the different-hemifield advantages in Experiments 1 and 2 were of virtually identical magnitudes, even though the different-field stimuli in Experiment 1 (i.e. diagonal presentation) also had a different vertical alignment, whereas the different-field stimuli in Experiment 2 (i.e. horizontal presentation) had the same vertical alignment. Clearly, the mere fact that stimuli were aligned horizontally cannot account for our results.

From one perspective, the results of Experiments 1, 2 and 4 are puzzling: different-hemifield stimuli presumably require the brain to transfer a representation of one stimulus to the other hemisphere for a comparison, whereas same-hemifield stimuli do not. Thus, we might have expected subjects to require more time to compare stimuli presented in the different fields. Nevertheless, our results are consistent with other findings in the literature. For example, DAVIS and SCHMIT [4] presented two gratings in the same hemifield or in different hemifields. Each grating could be oriented horizontally or vertically, and the subjects were to decide whether the gratings were the same or different. Much to their surprise, they found that subjects discriminated stimuli faster when they appeared in different hemifields than when they appeared in the same hemifield.

The results of an experiment by SKELTON and ERIKSEN [35] also bear on the present findings. In their experiment, eight letters were presented in an octagonal arrangement centered about a fixation point; two of the eight letters were located on the vertical meridian, and two on the horizontal meridian. The task was to determine whether two cued letters were identical. The subjects most quickly judged adjacent and diametrically opposite pairs, and most slowly judged pairs that were separated by the second smallest distance (of four possible distances). Skelton and Eriksen concluded that RT varied non-monotonically with spatial separation, and claimed that the angular orientation of stimulus pairs and inter- vs intrahemispheric processing could not account for the effect of distance. However, angular orientation was confounded with hemisphere in their experiment: when targets were aligned vertically, the two stimuli initially were processed by the same hemisphere (i.e. when cued letters appeared both on the left or both on the right side of the octagon) or simultaneously by both hemispheres (i.e. when cued letters appeared on the vertical meridian). In contrast, when targets were aligned horizontally, the two stimuli were always initially processed by separate hemispheres. Thus, some of their results may in fact be consistent with results observed in the present experiments.

Finally, two experiments by LIEDERMAN *et al.* [20] also reinforce the present findings. They presented pairs of words bilaterally or unilaterally (and hence initially to a single hemisphere), and asked subjects to discriminate among categories. The subjects evaluated bilateral pairs as fast as the better of the single-hemisphere conditions (i.e. the left hemisphere) and significantly, faster than their average. This result was independent of effects of distance, visual angle and compatibility with reading biases. This finding, then, suggests that each hemisphere can work independently during at least some phases of perceptual encoding, as is also implied by our results.

It is also possible that the different-hemifield advantage is related to LABERGE and BROWN'S [19] attentional range effect. An explanation of this finding hinges on the idea that each hemisphere retains a separate pool of attentional capacity (cf. [11, 27]). In the experiments reported by LABERGE and BROWN [19], subjects were led to expect a target to appear over a larger range by a stimulus string that subtended a larger visual angle. Because subjects were fixating at the center, stimuli that subtended larger angles included more

material in each hemifield. Thus, each hemisphere may have been able to contribute more processing resources to relatively high-level processing—not simply figure/ground segregation—not only because task difficulty increased, but also because of the widened range.

The notion of variable resources in attention is not new [17, 22], but it gains credence from recent neurophysiological findings. SPITZER *et al.* [36] found that the amount of effort or attention required by a task changes the responses of cells in the cortex. Specifically, they reported that cells in area V4 (a visual area known to have its responses modulated by spatially directed selective attention [21]) showed enhanced responses and sharpened selectivity for stimuli when the task required more effort or attention (i.e. the same stimuli in a more difficult discrimination task involving orientation or color).

The different-hemifield advantage we found could also reflect a second kind of hemisphere-specific processing that has been documented by neurophysiological findings. These findings pertain to response properties of cells in the inferior temporal cortex (area TE), an area known to be involved in shape perception (see for example [13, 29, 41]). SATO [29] recorded the responses of cells in this area to effective but unattended stimuli while the monkey performed a visual pattern discrimination task. He found that the attentional gating (i.e. suppression of response to effective but unattended stimuli) previously reported by MORAN and DESIMONE [21] occurred only when the attended stimulus was restricted to the contralateral part of the cell's receptive field. An attended stimulus in the contralateral part of the cell's receptive field suppressed the cell's response to other effective stimuli in its receptive field, whereas an attended stimulus in the ipsilateral part did not.

Thus, the advantage we found for different-hemifield presentation may not reflect additional resources, but rather a lack of inhibition. That is, the different-hemifield advantage may arise not because of competition for hemisphere-specific resources, but rather because of less intrahemispheric interference. Both explanations, however, postulate the existence of hemisphere-specific processes, and further research seems to support such an hypothesis [30, 31].

In summary, the present findings suggest that two stimuli in the same visual hemifield engender competition for common processing structures and/or evoke intrahemispheric inhibition. Hence, subjects can compare stimuli more quickly when they are initially processed by different hemispheres.

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REFERENCES

1. ALLMAN, J., MIEZIN, F. and MCGUINNESS, E. Direction- and velocity-specific responses from beyond the classical receptive fields in the middle temporal visual area (MT). *Perception* **14**, 105–126, 1985.
2. BECK, J. Perceptual grouping produced by line figures. *Percept. Psychophys.* **2**, 491–495, 1967.
3. BERGEN, J. R. and JULESZ, B. Parallel versus serial processing in rapid pattern discrimination. *Nature* **303**, 696–698, 1983.
4. DAVIS, R. and SCHMIT, V. Timing the transfer of information between hemispheres in man. *Acta psychol.* **35**, 335–346, 1971.
5. DESIMONE, R. and GROSS, C. G. Visual areas in the temporal cortex of the macaque. *Brain Res.* **178**, 363–380, 1979.

6. DESIMONE, R., SCHEIN, S. J. and ALBRIGHT, T. D. Form, color, and motion analysis in prestriate cortex of macaque monkey. In *Study Group on Pattern Recognition Mechanisms*, C. CHAGAS (Editor), pp. 165–178. Pontifical Academy of Science, Vatican City, 1981.
7. DOWNING, C. J. and PINKER, S. The spatial structure of visual attention. In *Attention and Performance XI*, M. I. POSNER and O. S. M. MARIN (Editors), pp. 171–187. Erlbaum, Hillsdale, 1985.
8. EGETH, H. and EPSTEIN, J. Differential specialisation of the cerebral hemispheres for the perception of sameness and difference. *Percept. Psychophys.* **12**, 218–220, 1972.
9. ERIKSEN, C. W. and MURPHY, T. D. Movement of attentional focus across the visual field: A critical look at the evidence. *Percept. Psychophys.* **42**, 299–305, 1987.
10. ERIKSEN, C. W. and YEH, Y. Allocation of attention in the visual field. *J. exp. Psychol.: Hum. Percept. Perform.* **11**, 583–597, 1985.
11. FRIEDMAN, A. and POLSON, M. C. Hemispheres as independent resource systems: Limited-capacity processing and cerebral specialization. *J. exp. Psychol.: Hum. Percept. Perform.* **7**, 1031–1058, 1981.
12. FRIEDMAN, A., POLSON, M. C., DAFOE, C. G. and GASKILL, S. J. Dividing attention within and between hemispheres: Testing a multiple resources approach to limited-capacity information processing. *J. exp. Psychol.: Hum. Percept. Perform.* **8**, 625–650, 1982.
13. GROSS, C. G. Visual functions of inferotemporal cortex. In *Handbook of Sensory Physiology* Vol. VIII(3B), R. JUNG (Editor), pp. 451–482. Springer-Verlag, New York, 1972.
14. HUGHES, H. C. and ZIMBA, L. D. Spatial maps of directed visual attention. *J. exp. Psychol.: Hum. Percept. Perform.* **11**, 409–430, 1985.
15. HUGHES, H. C. and ZIMBA, L. D. Natural boundaries for the spatial spread of directed visual attention. *Neuropsychologia* **25**, 5–18, 1987.
16. JULESZ, B. and BERGEN, J. R. Textons, the fundamental elements in preattentive vision and perception of textures. *Bell Syst. tech. J.* **62**, 1619–1645, 1983.
17. KAHNEMAN, D. *Attention and Effort*. Prentice-Hall, Englewood Cliffs, New Jersey, 1973.
18. LABERGE, D. Spatial extent of attention to letters and words. *J. exp. Psychol.: Hum. Percept. Perform.* **9**, 371–379, 1983.
19. LABERGE, D. and BROWN, V. Variations in size of the visual field in which targets are presented: An attentional range effect. *Percept. Psychophys* **40**, 188–200, 1986.
20. LIEDERMAN, J., MEROLA, J. and MARTINEZ, S. Interhemispheric collaboration in response to simultaneous bilateral input. *Neuropsychologia* **23**, 673–683, 1985.
21. MORAN, J. and DESIMONE, R. Selective attention gates visual processing in the extrastriate cortex. *Science* **229**, 782–784, 1985.
22. NAVON, D. Attention division or attention sharing? In *Attention and Performance XI*, M. I. POSNER and O. S. M. MARIN (Editors), pp. 133–146. Erlbaum, Hillsdale, 1985.
23. NEISSER, U. *Cognitive Psychology*, pp. 46–104. Appleton-Century-Crofts, New York, 1967.
24. PETERSEN, S. E., ROBINSON, D. L. and KEYS, W. Pulvinar nuclei of the behaving rhesus monkey: Visual responses and their modulation. *J. Neurophysiol.* **54**, 867–886, 1985.
25. PETERSEN, S. E., ROBINSON, D. L. and MORRIS, J. D. Contributions of the pulvinar to visual attention. *Neuropsychologia* **25**, 97–105, 1987.
26. POMERANTZ, J. R., SAGER, L. C. and STOEVER, R. G. Perception of wholes and their component parts: Some configural superiority effects. *J. exp. Psychol.: Hum. Percept. Perform.* **3**, 422–435, 1977.
27. POSNER, M. I., SNYDER, C. R. R. and DAVIDSON, B. J. Attention and the detection of signals. *J. exp. Psychol.: Gen.* **109**, 160–174, 1980.
28. RIZZOLATTI, G., RIGGIO, L., DASCOLA, I. and ULMITA, C. Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia* **25**, 31–40, 1987.
29. SATO, T. Effects of attention and stimulus interaction on visual responses of inferior temporal neurons in macaque. *J. Neurophysiol.* **60**, 344–364, 1988.
30. SERENO, A. The role of the vertical and horizontal meridians in visual discrimination (in preparation).
31. SERENO, A. and KOSSLYN, S. Hemisphere-specific processing resources. *Ass. Res. Vis. Ophthalm.* **30**, 160, 1989.
32. SHULMAN, G. L., REMINGTON, R. W. and MCLEAN, J. P. Moving attention through visual space. *J. exp. Psychol.: Hum. Percept. Perform.* **5**, 522–526, 1979.
33. SHULMAN, G. L., SHEEHY, J. B. and WILSON, J. Gradients of spatial attention. *Acta psychol.* **61**, 167–181, 1986.
34. SHULMAN, G. L., WILSON, J. and SHEEHY, J. B. Spatial determinants of the distribution of attention. *Percept. Psychophys.* **37**, 59–65, 1985.
35. SKELTON, J. M. and ERIKSEN, C. W. Spatial characteristics of selective attention in letter matching. *Bull. Psychonom. Soc.* **7**, 136–138, 1976.
36. SPITZER, H., DESIMONE, R. and MORAN, J. Increased attention enhances both behavioral and neuronal performance. *Science* **240**, 338–240, 1988.
37. TREISMAN, A. and GELADE, G. A feature-integration theory of attention. *Cognit. Psychol.* **12**, 97–136, 1980.
38. TREISMAN, A. and PATERSON, R. Emergent features, attention, and object perception. *J. exp. Psychol.: Hum. Percept. Perform.* **10**, 12–31, 1984.

39. TREISMAN, A. M., SYKES, M. and GELADE, G. Selective attention and stimulus integration. In *Attention and Performance VI*, S. DORNIC (Editor), pp. 333–361. Erlbaum, Hillsdale, 1977.
40. TSAL, Y. Movements of attention across the visual field. *J. exp. Psychol.: Hum. Percept. Perform.* **9**, 523–530, 1983.
41. UNGERLEIDER, L. G. and MISHKIN, M. Two cortical visual systems. In *Analysis of Visual Behavior*, D. J. INGLE, M. A. GOODALE and R. J. W. MANSFIELD (Editors), pp. 549–586. MIT Press, Cambridge, Massachusetts, 1982.
42. VAN ESSEN, D. Functional organization of primate visual cortex. In *Cerebral Cortex*, Vol. 3, A. PETERS and E. G. JONES (Editors), pp. 259–329. Plenum Press, New York, 1985.
43. WURTZ, R. H., GOLDBERG, M. E. and ROBINSON, D. L. Behavioral modulation of visual responses in the monkey: Stimulus selection for attention and movement. *Prog. Psychobiol. Physiol. Psychol.* **9**, 43–83, 1980.
44. WURTZ, R. H., RICHMOND, B. J. and NEWSOME, W. T. Modulation of cortical visual processing by attention, perception, and movement. In *Dynamic Aspects of Neocortical Function*, G. M. EDELMAN, W. E. GALL and W. M. COWAN (Editors), pp. 195–217. John Wiley and Sons, New York, 1984.
45. YANTIS, S. On analog movements of visual attention. *Percept. Psychophys.* **43**, 203–206, 1988.
46. ZEKI, S. Colour coding in the cerebral cortex: The reaction of cells in monkey visual cortex to wavelengths and colours. *Neuroscience* **9**, 741–765, 1983a.
47. ZEKI, S. Colour coding in the cerebral cortex: The responses of wavelength-selective and colour-coded cells in monkey visual cortex to changes in wavelength composition. *Neuroscience* **9**, 767–81, 1983b.