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Theory of Attentional Operations in Shape Identification

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This article presents a theory of selective attention that is intended to account for the identification of a visual shape in a cluttered display. The selected area of attention is assumed to be controlled by a filter that operates on the location information in a display. The location information selected by the filter in turn determines the feature information that is to be identified. Changes in location of the selected area are assumed to be governed by a gradient of processing resources. Data from three new experiments are fit more parsimoniously by a gradient model than by a moving-spotlight model. The theory is applied to experiments in the recent literature concerned with precuing locations in the visual field, and to the issue of attentional and automatic processing in the identification of words. Finally, data from neuroanatomical experiments are reviewed to suggest ways that the theory might be realized in the primate brain.

The identification of shapes and objects in the environment plays an important adaptive role in our daily, moment-to-moment activities. A typical visual scene contains many objects, but there is a limit on the number of objects that we can process at one time. This limitation implies that, at some stage or stages in the information flow through the system, the information arising from some objects must be momentarily excluded from processing. This exclusion from processing may occur by operations that either enhance the information from a target object, or by operations that suppress the information from the distractor objects, or by operations that do both. Described in this manner, exclusion from processing closely resembles what traditionally has been termed *selective attention.*

The notion of selective attention gained a foothold in the mainstream of psychology in the late 1950s, particularly through the influence of Broadbent's (1958) filter theory and Guthrie's (1959) revision of his learning theory ("what is being noticed becomes the signal for what is being done"). Soon afterward, a controversy arose concerning whether the selection process occurs early (Broadbent, 1958) or late (Deutsch & Deutsch, 1963; Norman, 1968) in the flow of information. The two contrasting views of the locus of selection can be seen in theoretical issues raised two decades later (for reviews, cf. Broadbent, 1982; Johnston & Dark, 1986; Kahneman & Treisman, 1984; Shiffrin, 1988). A strong form of the late-selection theories assumes that all objects in a visual display (falling on an effective area of the receptor surface) are identified and that the selection process chooses the identified object that will be processed further (e.g., for storage or for determining an overt response). In contrast, a strong form of the early-selection theories assumes that the selection process operates prior to the identification process, so that the identification operations are applied only to the targeted object and not to the other objects in the scene.

The purpose of this article is to set forth a theory that describes how selective attention could operate early in visual processing to enable the identification of an object or shape when other objects or shapes are present. This theory does not rule out selection at later stages of the system (e.g., categorization of identified shapes and choice of response used); rather, it confines its concerns to how selection occurs in the early process of shape identification. In contrast to other current theories of attention (e.g., Shiffrin & Schneider, 1977; Sperling & Melchner, 1978; Treisman & Gelade, 1980), the theory in its initial formulation here deals only with cases in which the location of the target object does not require search.

The theory will be described in two parts. The first part of the theory indicates how a selected area in visual space can be chosen by sets of operations, both facilitatory and inhibitory, to enable the identification of an object. The second part of the theory describes how a change in the location of the selected area can be accounted for by a processing gradient and how the gradient can be integrated with the mechanisms of spatial selection discussed in the first part.

Our approach to the two problems of forming a selected area and changing the location of the selected area is first to ask computationally what selective operations must be performed if the system ultimately is to identify an object somewhere in the visual field. Then, data from three new experiments will be used to support a gradient model over a moving-spotlight model of how the selected area changes location across the visual field. Finally, relevant evidence from neuroanatomical experiments will be reviewed to indicate how domains of the theory may correspond to the anatomical architecture of the primate brain.

Theory of Selective Attention in Shape Identification

The general way that the selective process of attention is conceptualized here for identification tasks can be briefly illus-

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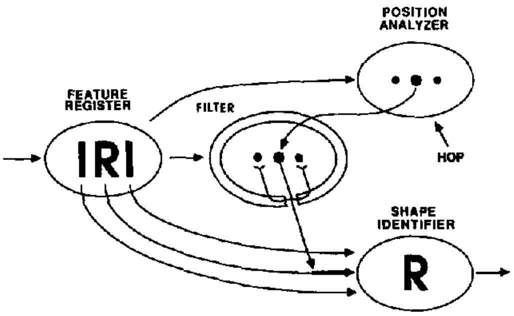

Figure 1. Schematic representation of the four domains of the theory assumed to produce the identification of a target shape when other shapes are located nearby. (HOP = higher order processes.)

trated by the following example. The display OR can induce an observer to perform one of three identifications: (a) the identification of the object on the left, O, (b) the identification of the object on the right, R, or (c) the identification of the combined object, OR. If we wish the observer to perform one of these three identification tasks, we must somehow influence the way the visual system processes the display. For example, if we instruct the observer to identify the object on the left, the visual system must momentarily exclude the right object from the identification process. If we instruct the observer to identify the object on the right, the system must momentarily exclude the object on the left from the identification process. Finally, if we instruct the observer to identify the display as a whole, the system must refrain from excluding either object from the identification process. Assuming that the attention operation is responsible for excluding inputs to the identification process, one could say that selective attention is needed in the first two cases but not in the third case. Therefore, selective attention is required for the identification of an object when other objects are present. We note that the display OR can also be viewed as the word OR, so that O and R can then be viewed as parts of the object OR. Thus, selective attention is also required when identifying a part of an object because other parts are present.

Overview of the Theory of Selective Attention in Shape Identification

We theorize that four domains of processing are required to select a particular object for identification out of an array of objects. The four domains of the theory and their interconnections are shown schematically in Figure 1. Suppose the task for the visual system is to identify the middle object of the three-object ensemble |R| that is displayed to a subject. The stimulus ensemble |R| enters the system at the domain termed *the feature register* (FR), and the identification of the object is represented by the output from the domain called *the shape identifier* (SI). The selection of the center object, R, for identification comes about by the operation of the other two domains shown in Figure 1.

The position analyzer and filter domains operate only on the location information output by the FR domain, treating objects as *blobs*. The SI domain operates only on the feature information output by the FR domain, treating objects as *shapes*. In this article we use the terms *object* and *shape* synonymously when they refer to the external stimulus. When reference is made to internal information corresponding to the object or shape stimulus, we distinguish between location information and feature information, such that representations based on location information are called *blobs* and representations based on feature information are called *shapes*.

The position analyzer (PA) domain selects the center of the three objects as a consequence of task instructions represented in higher order processes (HOP). This selection results in an increased rate of information flow from the center location of the three-object representation in the filter domain, which in turn causes a *channel* to open and enhance the stream of feature information of the object R flowing from the FR domain to the SI domain. In this way, the SI domain responds only to the feature information at the location of the center object.

With this overview of the theory in mind, we now examine the proposed characteristics of each of the four domains in more detail and highlight the important interactions between the domains.

Feature Registration Domain

The FR domain is assumed to represent feature and location information of the visual stimulus following the initial establishment of a sensory image on the retina. This early representation is assumed to contain subdomains that register locations of features such as lines, color, contour, motion, and depth. For purposes of identifying shapes, the feature information of lines (orientations, lengths, terminations, etc.; cf. Julesz, 1984; Treisman & Gormican, 1988) is assumed to constitute the input to the shape identification domain. Of course, under special conditions, an object may be detected on the basis of only one feature, for example, color, motion, or orientation of a single line (the "pop-out" effect). Such single feature detections are presumed to occur without participation of the shape identification domain, and the term *detection* will be used instead of the term *identification* for such cases.

Shape Identification Domain

We assume that the features that combine to form shapes must be presented to the SI domain in order for the shape (object) as a whole to be identified. Outputs from this domain may proceed to domains in which the shapes are categorized, judgments formed, and overt responses generated. For example, in the reading process, the output from the SI domain may be regarded as a bridge between perception of parts or wholes of word forms and their corresponding lexical categories that are stored in working memory (Estes & Brunn, 1987).

It is apparent that the human visual system cannot identify an unlimited number of objects simultaneously. We make the assumption here that the domain of shape identification performs only one identification at a time. The domain takes everything that is presented to it as a whole and then attempts to identify that whole by matching the feature input with a stored representation. For example, the ensemble |R| would not be identified because the ensemble, taken as a whole, does not constitute a (familiar) shape stored in the SI domain. Similarly, the ensemble VRY would not be identified; but if the flankers of the R were A and E instead of V and Y, then the resulting ensemble, ARE, would be identified by the SI domain because the ensemble, ARE, is stored there as a familiar shape. Thus, the SI domain is assumed to identify objects by *whole* processing.

It is important to distinguish whole processing from part processing in identification of shapes. If it were assumed that the SI domain identified simultaneously all of the (familiar) parts of a stimulus display presented to it, then when it is presented with the word STEAM, it should typically identify the nested word TEA as well as the word STEAM. But when one is presented with a familiar word, one seldom identifies a word that is nested within it. By analogy, it is presumed that one also does not identify the letters within a familiar word, at least at the moment the whole word is being identified.

If the SI domain is to identify the word TEA within STEAM by whole processing, the five letters of STEAM must first be segregated (prior to an identification event) into three objects, consisting of each outside letter and the group of three inside letters. When the feature information from just the location of the inside three-letter group is fed into the SI domain, the nested word TEA can then be identified. Similarly, to identify a letter of the word STEAM, the stimulus must first be segregated into the five letter objects, and the feature information from just the location of one object is fed into the SI domain. Thus, one object is identified at a time.

If, on the other hand, the SI domain acted as a part processor, then when presented with the display STEAM, it should simultaneously process and output the identities of the words STEAM, TEA, TEAM, and AM, as well as each of the five constituent letters. Thus, many objects are identified at a time. Such a multiple output is confusing for purposes of further processing, such as categorizing STEAM or responding overtly to it, and therefore, some way must be found to select STEAM from the other shapes after they all have been identified. Thus, for part processing it would seem that the confusion following identification of parts would have to be eliminated by a late selection operation, whereas for whole processing, any confusion preceding identification of a given shape is eliminated by an early selection operation, as in the present theory.

Another consequence of this gestaltlike view of shape identification is that it should be difficult if not impossible to identify simultaneously two shapes presented in separate locations. There is some evidence that this is the case (e.g., Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980). Thus, the bottleneck in identifying objects is assumed here to be determined by the characteristics of the shape identifier, and it is because of this limitation on the identification domain that the operation of attentional filtering seems to be required.

Filter Domain

We now consider the operation of the filter domain. When we present |R| to the FR domain and thereby route feature information to the SI domain (as shown in Figure 1), the filter is induced to amplify the information flow representing the center target relative to the flankers. The filter domain is assumed to consist of two main parts, a spatiotopic map, termed the *filter map,* and a spatiotopic structure that opens to form a channel, termed the *filter mechanism.* The representations in the map of the filter are indicated in the diagram by dots or blobs to denote that location information and not feature information is entered into this domain. The filter map represents the locations of features in the FR domain, and the filter map is linked topographically with the connections from the FR domain as they enter the SI domain. The inputs from the FR domain combine with inputs from other domains to raise the information flow at a particular location in the filter map to a rate high enough to open a channel in the filter mechanism.

For accomplishing the selection of the feature information corresponding only to the letter R in the object |R| of the present example, the number of apertures or channels in the filter must be restricted to one. The opening of more than one filter channel would result in presenting more than one item to the SI domain at one time, and unless the ensemble of items constitutes a familiar shape, the SI should fail to produce an identification response. For example, suppose that presenting the object /R///O/ could, under certain circumstances, briefly open two separate channels corresponding to the locations of the letters R and O, with the result that the feature information corresponding to RO enters the shape identifier. In this case, the shape identifier should fail to identify the object, because the shape, RO, has no stored representation there. In consequence, we would expect the system then to close one channel and thereby attempt to identify one of the two letters, and then close that channel and open the one at the other object's location to identify the other letter. On the other hand, if the order of letters in the object were reversed (i.e., /O///R/) producing the familiar shape OR, then it is conceivable that the shape identification domain could produce an identification event based on the two open channels in the filter.

We now describe an inhibitory network that is assumed to operate within the filter mechanism to form a selected area of attention (i.e., a channel). Suppose that a target-flanker ensemble such as KRB is presented to an observer. When the position analyzer domain selects the middle letter position, the flow of information from that location in the filter map begins to increase relative to information flow from adjacent locations. Subsequently, the filter mechanism begins to suppress the information flow from the flanker locations. As the PA domain further increases the information flow from the target location, the inhibitory filter mechanism further suppresses the output from the flanker locations. Thus, the lateral inhibitory network of the filter mechanism successively amplifies the initial differences in information output between the target and flanker locations. Eventually, output from the flanker locations is so reduced (or even eliminated) that the dominant information flow from the filter is from the target location. At this point a channel is said to have opened in the filter. The information flow from the target location in the filter now serves to enhance the flow of feature information from the FR to the SI domain, as shown in Figure 1.

One might assume alternatively that the process of opening a channel of a size corresponding to the area of the target could be effectively produced without inhibition simply by increasing the flow of information from the target location over that of the flanker locations. However, the flow of information could initially be very high at all three letter locations of the ensemble, and a ceiling on the rate of flow at any location would prevent the formation of the difference in information flow between target and flanker locations needed to open a channel in the filter mechanism. Instead, we assume that lateral inhibition progressively builds at the flanker locations as a result of the enhancement of information flow at the center location from the position analyzer domain. This kind of sharpening of differences in information flow between target and surround would seem to be effective for identifying a relatively small object in a cluttered field by fine-tuning the shape of the filter channel so that it permits the enhancement of just the target feature information entering the SI domain.

The inhibitory network in the filter mechanism is assumed to be active at all times in the awake subject. Thus, the opening of a channel at a particular location requires a flow of information that overcomes the existing inhibition. Once achieved, the channel opening would be expected to be maintained only briefly because the prevailing inhibitory nature of the filter mechanism should proceed to close off the channel quickly. Such short durations of channel openings would not seem to be an important limitation on identifying a shape because an identification would require only a short time to complete, once the appropriate inputs to the SI domain are delivered. Indeed, the inhibitory processes within the filter may well induce considerable channel fluctuation during a 200-ms exposure of a stimulus without appreciable effect on the identification of the stimulus, providing that, at some moment, the filter channel assumes the appropriate size and location just long enough to induce an identification event to take place in the SI domain.

Position Analyzer Domain

Thus far we have described three domains that seem necessary on computational grounds to identify the shape of a visual target flanked by other stimuli, namely the feature register, the shape identifier, and the filter. At this point in the exposition of the theory we note that, although the filter can produce a difference in the target relative to its flankers in the flow of feature information from FR to SI, it has no means itself of determining that the information located at the center of the three items is the location at which the filter is to operate to pass information to the SI inputs. We assume that the selection of the location of a target within the spatiotopic map of the filter is produced by a fourth domain, the PA domain, which is object centered and responds to higher order routines that direct it to select specific parts of the stimulus object. Such a domain, shown in Figure 1, responds to inputs from higher order processes that deal in goals and beliefs of the subjects, presumably in accord with task demands and instructions. An example of a goal would be the identification of the center letter in VRY, or the center letter in the word TORCH. In these cases, the position analyzer produces an increase in the flow of information from the center position of the stimulus ensemble represented in the filter map. The problem of specifying the operations constituting higher order routines that relate the positions of shapes within a display (e.g., a routine that locates the middle of a group of objects) may be of considerable complexity, and the reader is referred to the account of processing of relations given by Ullman (1984).

The domain that analyzes (or relates) positions within an object is more open-ended conceptually than the other domains described thus far because of the globally specified input from HOP. It would seem reasonable to tolerate this kind of ambiguity for the present, particularly because the theory at hand is not intended to be a complete theory of all processes involved in identifying a shape, but only a theory of attentional processes involved in identifying a shape.

The functional importance of the PA domain in determining an object's location within a group of objects (or a part's location within an object) perhaps can be made more explicit by considering how the domain would operate in a task whose goal is to judge the location of a particular object, in contrast to the present task, whose goal is to judge the identity of an object in a particular location. Suppose a subject is asked to judge where the letter R is located in the three-item ensemble VYR, when the ensemble can appear in one of five locations across head-centered visual space. In this task, the output to the overt response would come from the PA domain instead of from the SI domain. The processing events leading to this output from the PA domain are assumed to be as follows. When the stimulus VYR is presented, representations are passed from the FR domain to the filter map as three unidentified objects (blobs). The filter domain (under control from the PA domain) then opens a channel at each object's location in turn, and selects feature information of the corresponding letters to enter the SI domain. The letter R has already been cued, top-down, by HOP to the SI domain as the criterion target, so that when a match occurs in the SI domain, this domain returns that information to the filter map. The increased information flow from this location of the filter map is then passed on to the corresponding location in the PA domain. The PA domain then produces a location judgment response, and signals the overt response mechanism to deliver an overt response. This theoretical account of the role of the PA domain in a location task uses the mechanisms of the theory shown in Figure 1, with the added assumptions that arrows connecting the filter, PA, and SI domains go in both directions, that HOP also activates the SI domain, and that a right-pointing response arrow be attached to the PA domain in the same manner as it is attached to the SI domain.

Thus, the output from the PA domain can inform higher order domains where a target object is, whereas the output of the SI domain tells these domains what the target object is. The mechanism that enables the system both to locate an object and to identify an object is the filter. Therefore, one could say that the filter mechanism selects a specific area of the visual field for specialized processing of location information by the PA domain and for specialized processing of feature information by the SI domain.

Effects of Varying Target and Surround Similarity

One of the major empirical variables that affects the rate of filtering is the similarity of a target object to the distracting objects located in its neighborhood. The experiments to be reported later in this article manipulate this variable for the purpose of testing a gradient model of attention change against a moving-spotlight model. It is important, therefore, to understand how the variable of target–flanker similarity affects rate of filtering in the present theory.

The way that different levels of target–flanker similarities come to be represented in the filter map is from projections of target–flanker representations in the feature registration domain. In the FR domain, locations of features are represented in a spatial map, and lateral connections exist between representations of features, at least within immediate neighborhoods. Neighboring representations of features that are similar are assumed to inhibit each other's information output, and the more similar they are, the more they inhibit each other. For example, the stimulus ensemble KRB is assumed to produce more equal rates of information flow from the target and flanker locations than the ensemble |R|, because the features of the flankers in KRB are more similar to the target R and will inhibit R as well as each other. In contrast, the stimulus ensemble |R| will produce a higher rate of information flow from the target locations than from the flanker locations because the features of the flankers in |R| will inhibit each other more than they will inhibit the target R. The proposed interaction between features of neighboring objects is reminiscent of Estes' interactive channels model (Estes, 1972, 1975, 1982; also cf. Bjork & Murray, 1977; Wolford & Chambers, 1983). Neuroanatomical evidence from single-cell recordings in the monkey visual cortex that support this assumption will be described in the final section of this article. The differing rates of output from the three locations (which can be imagined as a *profile* of three bars of a bar graph drawn over the target and flanker locations) are passed directly to the filter map.

Generally, this difference in information flow between target and flankers is not great enough for the lateral inhibitory filter mechanism to effectively produce a channel at the target location. The PA domain is required to further increase the rate of information flow from the target location. How much further input from PA is required depends on the initial target–flanker differences. It follows that the greater the target–flanker similarity (i.e., the flatter the information-flow profile), and thus the more additional input from PA required to open a channel, the longer it will take for a channel to open.

A consequence of this characterization of similarity or saliency of the target relative to its surround is that the filter channel can be attracted directly to the location of the target (without assistance from the PA domain) when it contains a unique feature or features (e.g., attending to the letter V in a group of Os), because a unique feature could produce a sufficiently sharp contrast in the target–flanker flow profile to open a channel. This account contrasts with accounts that assume that attention comes to be focused on a unique feature indirectly by scanning locations of the visual field (e.g., Duncan, 1981).

Priming of a Feature in the Feature Registration Domain

In the foregoing section, we gave a theoretical description of how the relative rate of information flow from a feature representation in a specific location of the feature registration domain can be increased by interactions with the representations of features of neighboring objects. The flow of information from a feature location can also be increased by top-down priming. To illustrate feature priming, we choose a color as an example, but the account is intended to hold for features such as an oriented line or a direction of movement of an object.

If a subject is told prior to a display onset that the target shape is red, then a series of events occurs that results in the opening of a channel at the location of a red object (or the opening of several channels at the locations of several red objects). The series of events begins with the instructed priming of the color red. We would represent this event in a color analyzer domain that is analogous to the position analyzer domain in that it is directed by HOP in response to task instructions (e.g., "identify the red target in the display" or "the target letter is red"), and it in turn increases information flow in color maps in the feature registration domain. When red is selected in the color analyzer domain, the flow of information is increased at the location of an incoming red stimulus. This location information is projected to the filter map where it opens a channel in the filter mechanism corresponding to the location of the red stimulus. Because the filter channel is aligned also with other features at the location of the red stimulus, the shape of the red stimulus (e.g., a letter) comes to be identified. That is, the filter mechanism enhances the flow of information (from FR to SI) from all features at the location of the red object because the filter itself represents only location information without regard to the specific features present at a given location. In view of these assumptions, one could say that priming the color of a target (in a background of targets of another color) facilitates the processing of the object's other features.

When a filter channel is aligned on a red target, the channel should not remain open for long because of the prevailing inhibitory property of the filter mechanism. But if only one red target is in the display, the brief channel opening could be sufficient to enable an identification event in the SI domain. If several red targets are in the display, the PA domain will be required to select one location at a time in the filter map to produce target identifications. The PA domain, it is assumed, represents the group of locations corresponding to the several red targets via direct connections from the FR domain (cf. Figure 1) that pass on the relatively higher rates of information flow at those locations (e.g., Egeth, Virzi, & Garbart, 1984; Pashler, 1987). We would assume that cuing of oriented lines operates in a similar manner to the cuing of colors, beginning with a line orientation analyzer at a higher level that selects lines of a particular orientation. Thus, these examples of cuing colors and line orientations emphasize that the filter domain itself does not initiate the location of attention, even with primitive features such as colors and oriented lines, but rather is responsive to activity in these other domains.

The foregoing discussion of the operations of a color analyzer domain provides a context for describing how the present theory would treat the phenomenon of *preattentive processing* (Julesz, 1984; Koch & Ullman, 1985; Treisman, 1985) in the detecting and locating of simple features in a display. Much as the PA domain is assumed to signal judgments of location to higher order processors, the color analyzer domain is assumed to signal judgments of color in a task in which the subject is to determine the color of a red or yellow dot in a display of black dots. The judgment that a red dot was present could be made without the involvement of the filter (i.e., preattentively) because the representation of red in the FR domain is projected directly to the color analyzer domain, and the color analyzer domain can output a judgment of color to the overt response mechanism. But if the location of the red dot (among other dots) were also to be judged, then the participation of the filter would be required because a specific location in the PA domain must be selected to deliver a location judgment. The filter would then be needed in order to block information from the other locations, so that the location information of the red dot in the FR domain induces the filter to pass the information of the red dot's location to the PA domain. Thus, detection of the presence or absence of a feature such as a color or a line of a particular orientation in an array of contrasting features may bypass the filter, but judgment of the location of an object among other objects would seem to require the filter, particularly when the other objects are located nearby. For the present case, in which more than one object is displayed, location is not treated as a feature in the same way as color and line orientation (cf. Nissen, 1985) because location information provides the basis, within the filter map, by which features are selected, and not vice versa. This does not imply, however, that locations in space cannot be cued. We will discuss the cuing of locations later in this article under the topic of applications of the theory.

Top-Down Versus Bottom-Up Control of Filtering

The domains of feature registration and position analyzer can be contrasted in the ways in which they control the formation of a channel in the filter, and thus control the rate of filtering. The input to the filter from the FR domain may be said to *attract* attention, whereas the input to the filter from the PA domain *directs* attention. These two sources of attentional control resemble Milner's (1974) distinction between extrinsic attention and intrinsic attention.

A target object that is displayed in isolation or that contains features that are highly dissimilar to features of neighboring objects, produces in the FR domain a relatively large difference in information flow from the location of the target object compared with its surround, as discussed previously in the section on the effects of target–surround similarity. When this difference is passed to the filter map, it influences the rate of forming a channel at the location of the target object. If the difference is sufficiently sharp (e.g., representing the abrupt luminance change between a letter and a blank surround) it could open a channel in the filter without further input from the PA domain. Such strong bottom-up control on the channel location is illustrated by the abrupt onset of a bar marker that cues the location of a letter target in an array of letters positioned in a circle, a procedure used by Eriksen and his colleagues (e.g., Eriksen & Hoffman, 1972) and by Jonides (1981). Other examples of experimental procedures that fall into this category of attracting attention are the dot used by Tsal (1983), which cued the expected location of a target along a horizontal line, and the illumination of a square in one of the visual hemifields used by Posner (1980), which cued the expected square in which an asterisk appeared.

In contrast to the attracting of attention from the FR domain, attention may be directed from the PA domain by top-down processing. Examples of this case are given by the presentation of an arrow in the center of a display that directs the subject to attend to the position of an item (e.g., a letter) that is displayed (or is about to be displayed) on the periphery of a circle (Jonides, 1981) or to the position of a square located to the right or left of the arrow (Posner, 1980).

A further illustration of the contrast between top-down and bottom-up controls on the attention filter is given by attempting to read the following: "Rea dingthi si shard." The theory assumes that the FR domain registers four separate objects from this sentence display, corresponding to the four groups of letters, on the basis of the sharp changes in luminances at the boundaries of the letter groups. The spatial locations of these four objects are copied to the filter map and also to the map in the PA domain. Because the task is to "read" the groups of letters, the PA domain will be driven by a learned reading routine (from higher order processes) to select the locations of the four objects in the filter map one-by-one, from left to right. When the location of the first object is selected in the filter map, and the corresponding channel location is opened, the feature information selected to enter the SI domain is Rea. This feature ensemble produces no identification response by the SI domain because there is no stored representation for it to match. Similarly, when the filter channel is aligned to the locations of the other three groupings of letters, no identification responses are emitted by the SI domain. The PA domain must now be driven by a different routine from higher order processes by which it selects locations in the filter map. It must analyze each of the four groupings in terms of their constituent parts, that is, in terms of the letter objects, and simultaneously select letter locations that exist within and/or between the initial four groupings, until a combination of letters results in an appropriate identification response by the SI domain. Thus, in this example, the top-down grouping routines of the PA domain must work against the groupings of letters that are determined by the bottom-up luminance changes in the FR domain because the FR-driven feature groupings do not induce the filter to produce appropriate identification responses by the SI domain.

Theory of Spatial Changes in Selective Attention

Before introducing the theoretical domain that is intended to account for spatial changes of attention, we describe the psychophysical procedure used in our laboratory to measure attentional change across the visual field, in order to provide a context for the kinds of assumptions to be made.

Measuring Spatial Changes of Attention

The experimental procedure we used for measuring changes of location of the selected area typically involves three events in a trial (LaBerge & Brown, 1986). The first two events are intended to establish the initial location and size of the selected

Table 1
Shape Identification Task: Narrow-Attention Condition

<table>
<tr><th>Event</th><th>Positive stimuli</th><th>Negative stimuli</th></tr>
<tr><td>Warning signal</td><td>***#***</td><td></td></tr>
<tr><td>First target</td><td>585S858</td><td>vs. 5855858, 5858858, e.g.</td></tr>
<tr><td>Second target</td><td>|R|</td><td>vs. |P|, |Q|</td></tr>
<tr><td>Locations</td><td>. . . . .</td><td></td></tr>
<tr><td>Instruction</td><td colspan="2">Press the button only when S is followed by R.</td></tr>
</table>

area, and the third type of event induces the area to change its location. If we are to measure the change of location of the selected area it would seem critical that we carefully control the location and size of the area before its location changes.

In Table 1 is shown a typical sequence of trial events. The first event, termed the *warning signal*, displays the location and width of the target item expected in the second event. The second event, termed the *first target*, presents a target at the center position, surrounded by items having a high degree of similarity to the target. To ensure identification of the shape of the first target, catch trials are sometimes presented that replace the target with one of the surrounding items. The third event, termed the *second target*, presents a probe object at one of several locations in the visual field at or to the left or right of the first target's location (the probe appears with equal frequency in each location). The second target object consists of a familiar shape with other shapes flanking it. The reason that the second target shape is flanked by other shapes is to ensure that the filter is involved in selecting the center shape from the flanking items because the filter is not necessary for the identification of an unflankered familiar shape. Presenting the target shape with flankers is presumed to require the filtering of the flankers prior to identification of the target (so long as the whole target–flanker ensemble has not itself become familiar through many exposures). In order to ensure that more than one of the features of the target shape are processed by the subject, other shapes are occasionally substituted for the second target shape. For example, a target R may be replaced by the negative targets P or Q (with the same flankers as the R target). Note that the negative targets are chosen so that they share features with the positive target in such a way that identification of the positive target requires more than one feature (LaBerge, 1973; Treisman & Gelade, 1980). The strings of flanking items in the warning signal and first target extend across the range of second target locations in order to provide approximately equal premasking effects on all second targets.

Thus, during the warning signal, the subject is presumed to establish a selected area of a particular size and location in anticipation of the target item to be presented in the center of the string of the next display. We typically assign a relatively long exposure time for the warning signal (e.g., 750 to 1,250 ms) to allow time for the system to align and stabilize the selected area. The first target contains an object of a specified size that appears at a location anticipated during the warning signal. Its duration is typically short, 50 to 150 ms, depending on the type of target, such that there is just enough time for identification of the target. If the duration of the first target is much longer than the time needed to process its identification, then there will be time for the selected area's location and size to fluctuate before and after the identification event. The duration of the second target (the third display) should be long enough to ensure a high level of accuracy, but not so long as to allow eye movements (i.e., less than 250 ms) because eye movements would complicate the interpretation of the reaction time measure.

When a subject performs an experiment with the trial events of Table 1, the subject is required to press a button when the letter S (located in the center) is followed by an R (in any of five horizontal locations). The resulting reaction-time (RT) curve has a V shape, as illustrated in the upper part of Figure 2. We interpret this curve to indicate that the time to change the location of the selected area from the center to a point to the right or left of center is an increasing function of the spatial separation of the two points. The V-shaped reaction-time curve also has been obtained for target ranges of 0.9° to 4.3° on each side of center (LaBerge & Brown, 1986) and for slightly different procedures in which only two events occur on a trial (LaBerge, 1983).

As a control condition, the initial area of attentional selection was made as wide as the range of probe locations (i.e., five letter spaces) so that no shift of the location of attention would be required when the probe appeared. If no shift of location occurs, there should be no V shape to the curve (discounting effects of variations in retinal sensitivity). We chose as the first target a five-letter given name (e.g., STEVE, BETTY) and prefaced it with a warning signal that clearly marked the five center locations (e.g., *#####*), as shown in Table 2. The negative, first target items were five-letter names of kitchen objects, such as STOVE and TABLE. All second target probes were given within the area corresponding to the size of the five-letter word. The resulting reaction-time curve to the second target probes is shown in the lower part of Figure 2. Because in this case reac-

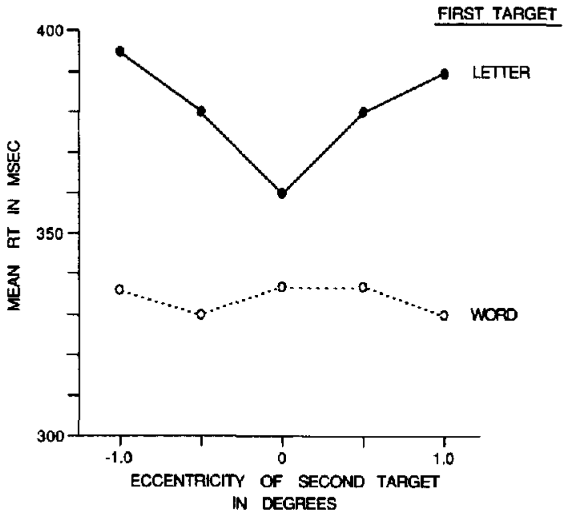

Figure 2. Mean reaction times to the second target, |R|, as a function of its location, given that the first target was a single letter at the center of the field (upper curve) or a five-letter word at the center of the field (lower curve). (Data are from 6 subjects.)

Table 2
Shape Identification Task: Wide-Attention Condition

Event	Positive stimuli	Negative stimuli
Warning signal	*######*	
First target	*BRUCE*	vs. *TABLE*, *CHAIR*
Second target	|R|	vs. |P|, |Q|
Locations	. . . . .	
Instruction	Press the button only when a given name is followed by |R|	

tion time to the probe does not differ as a function of location, we concluded that the onset of the probe produced no change in the location of the selected area. Of course, to process the filtering of the probe, the size of the selected area is presumed to have contracted from the size of the five-letter word to that of the single target letter of the probe. But the time to achieve the contraction is assumed to be independent of location of the probe within the range of five letters.

We now describe a theoretical mechanism that is intended to account for the change of attention indicated by the V curve of reaction time shown in the upper part of Figure 2.

The Gradient Model of Attention Change

The general concept of a gradient of processing is related to capacity notions of attention (Kahneman, 1973; Navon & Gopher, 1980; Shaw & Shaw, 1977; Wickens, 1978). More recently, the gradient concept has been applied to the way in which attention might be spread across the visual field (Downing & Pinker, 1985; LaBerge & Brown, 1986; Mangun & Hillyard, 1987; Podgorny & Shepard, 1983; Shaw, 1978; Shulman, Wilson, & Sheehy, 1985). The gradient view of attention adopted in the present theory assumes that nothing is moved across the visual field, but that a distribution of processing resources across the field affects the rate at which filtering will take place at a particular location. In the task described in Table 1 that produces the V curve in Figure 2, we assumed that a peak forms in the gradient distribution during the warning signal as the subject concentrates attention at the center location in anticipation of the first target. When the second target, |R|, appears in one of the five locations, its rate of filtering is affected by the value of the gradient at that location. For the present tasks, shown in Tables 1 and 2, the gradient is assumed not to change between the two target displays because the duration of the first display is brief and the interval between the two displays is very brief.

It has been observed that the amount of resources available to process a target object at a particular location is a function of the probability of the target's appearance at that location (e.g., Shaw, 1978; Shaw & Shaw, 1977). In the present procedure, however, the probability of target occurrence is equal across the five locations. What is assumed to set up a gradient peak at the center location is the high expectation (probability = 1.0) that the *first* target will appear at the center location, and this rather high-peaked gradient remains active at the onset of the second target, owing to the fact that the second target occurs immediately after the first target.

It is assumed that the V-shaped reaction-time curve is produced by the gradient operating on the filter mechanism. The gradient represents the expectation for the location of an object, and it is assumed to be contained in a new domain connected to the four domains of the theoretical scheme shown earlier in Figure 1. The additional domain, the location expectation domain (LE), is integrated schematically with the domains of feature registration, shape identification, filter, and position analyzer, as shown in Figure 3.

The LE domain is assumed to be organized topographically in head-centered coordinates, in contrast to the object-centered coordinate map of the position analyzer domain. The separation of the domains of location expectation and position analysis seems plausible because the location in visual space at which one may expect an object (e.g., VRY) to occur is independent of the spatial *position* of the target (e.g., R) within the boundaries of that object. Therefore, the gradient of location expectation may vary independently of the position of a target within a stimulus ensemble selected by the position analyzer. Moreover, locating the position of a part of an object (e.g., the center) requires sophisticated top-down routines that relate the parts of the object to each other, whereas locating the whole object in space can be more simply produced by the bottom-up information in the sudden onset of the object. Relating parts would seem to occur after the onset of a stimulus object, whereas expectation for a location would seem to operate prior to the onset of a stimulus object. Therefore, the domains of PA and LE would seem to be functionally separated for this reason as well.

However, the domains of PA and LE are functionally closely related, as illustrated by the way the warning signal establishes an expectation for a target at a given location. The warning signal provides the opportunity for the subject to anticipate the location of the first target, S, at the center location (cf. Table 1). This spatial anticipation is represented in the theory by the peak of a gradient at that location. The way that the warning signal prime produces a gradient peak involves the PA domain as follows (cf. Figure 3). During the warning signal display, a

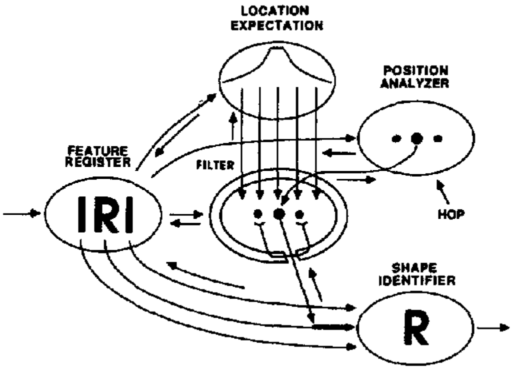

Figure 3. The five principal domains of the theory, showing control of the filter by the gradient in the location expectation domain, by the "centering" routine of the position analyzer, and by the feature register. (Coordinates of the location expectation domain, feature registration domain, and filter domain are head centered, and the coordinates of the position analyzer domain are object centered.)

filter channel is opened at the location of the asterisk by information flow from higher order processes operating from the PA domain. This information flow at the center location in the filter map is also projected to the LE domain, where a gradient of processing spreads outward from the center location. The gradient remains active over a period of time.

The gradient in the location expectation domain is assumed to be mapped in coordinates that are topographically connected to the map in the filter domain, such that values of the gradient at each location are projected to the filter map. Thus, tonic control from the LE domain influences the rate of processing at a given location in the filter map at the moment location information from a displayed object arrives from the FR domain. The filter channel then opens to the size of the entire object (e.g., VRY) because the luminance changes at the borders of this ensemble produce a sharp contrast between the ensemble and the surround. The channel size will have to be narrowed further if the flankers are to be filtered so that the shape identification domain responds only to the familiar shape in the center of the target object. To accomplish the narrowing of the channel, additional input is needed from the PA domain to select the appropriate position of the target within the object (e.g., the center position of VRY).

In Figure 3, the width of the flat sector at the center of the gradient in the LE domain is assumed to represent the width of the expected first target. For the two curves shown in Figure 2 (produced by the tasks in Tables 1 and 2), a narrow center sector of the gradient will generate the V curve and a wide sector the flat curve. The tails of the gradient curves are presumed to be shaped by the range over which the probes are expected to occur (LaBerge & Brown, 1986). The height of the center sector is conjectured at this time to be increased by factors (operating through the PA domain) that stabilize or restrict the fluctuations of the channel at the center location. An example of a factor that should restrict the fluctuation of the channel location is a short duration of the first target.

The possible forms that the gradient in the LE domain can assume is not restricted to a single mode, such as shown in Figure 3. Under circumstances in which second targets are highly likely to appear at two different locations, for example, with high probabilities at each of the outside locations shown in Table 1, the gradient could form two modes or peaks, with the locations of the peaks corresponding to the locations of the two outside target locations. The resulting reaction-time curve for this case of a split expectation should have the appearance of a bow, with lowest reaction times at the outside locations and higher reaction times toward the center. This hypothetical double-peaked gradient concentrates tonic flow of information at two locations of the filter map, with the result that the two corresponding channels can be opened more easily when an object is presented at either outside location. If the stimulus display happened to present a salient object at each of the two corresponding locations simultaneously, then conceivably both channels could open completely. Technically, one could then say that the filter had been divided. But this split of the attentional selection mechanism does not imply that the identification of the two objects will be processed simultaneously, because, as we discussed earlier, the shape identifier will not deliver an identification response to the combined feature inputs from the two locations, unless the combination happens to constitute a familiar shape. Consequently, the PA domain must operate to enhance information flowing through one of the channels so that the shape identifier can successfully operate on the features of only one of the objects.

Formal Treatment of the Gradient Model

The RT equation for the proposed gradient model is as follows:

$$\mathrm{RT}(x) = C_i s(x)/g(x) + T_r, \qquad (1)$$

where x denotes the location of the second target, $g(x)$ denotes the value of the gradient at location x, C_i denotes the target–flanker similarity factor, and T_r denotes residual processing time (the time required to register the stimulus in the sensory system and to generate an overt response). The eccentricity factor, $s(x)$, denotes the visual eccentricity or acuity factor and represents the fact that retinal sensitivity (or acuity) decreases as target locations are more eccentric to the fovea (Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987; Osterberg, 1935). The eccentricity factor may operate also at higher levels in the visual system. Thus, when attention is concentrated at the center of the eye and a target is presented away from center, the time to process the target is expected to increase simply because the sensitivity of the visual system decreases with increasing distance from retinal center. Therefore, we assume that the effect on reaction time due to the eccentricity factor is an increasing function of x. The eccentricity factor, $s(x)$, acts as a scale multiplier in Equation 1.

The way that C_i represents target–flanker similarity in Equation 1 is based on the assumption, developed in the earlier section on effects of target–surround similarity, that the higher the target–flanker similarity, the less the contrast between the rates of information flow at the locations of the target and flankers in the FR and filter maps (i.e., the flatter the profile). High target–flanker similarity requires more input from PA than low target–flanker similarity to open a narrow channel at the target location and filter out the flankers. As an example, suppose that the stimulus ensemble, |R|, is presented to the subject. The relatively low similarity between the target R and its vertical line flankers produces a profile of information flow across the three locations within the ensemble that is relatively high at the center (target) position and low on either side. This profile is projected to the filter map. Because this contrast between rates of information flow at target and flanker locations is not sufficient by itself to induce an opening of a narrow channel corresponding to the width of the target R, the PA domain increases information flow from the target position in the filter map. As the rate of flow increases at the target position, the rates of flow at the surrounding flanker locations decrease, owing to the lateral inhibitory links between these locations (as described previously in the section on the filter). If, instead of |R|, the ensemble KRB is presented to the subject, the high target–flanker similarity of this stimulus will require even more input from the PA domain to produce the contrast in flow rates between the target and flanker locations necessary to open a narrow channel

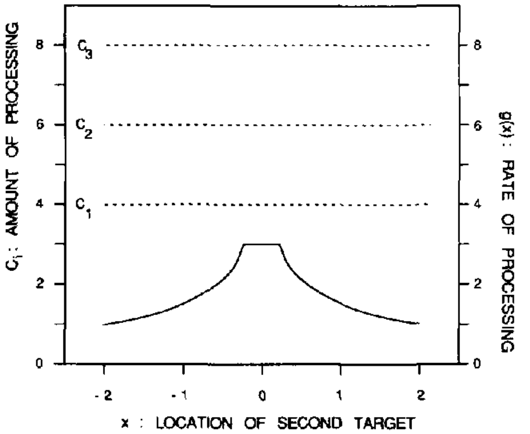

Figure 4. Illustration of a gradient of rates of processing, defined over a horizontal range of locations of a target stimulus. (Each of the three dashed lines at the top represent, for a particular degree of target–flanker similarity, the remaining amounts of processing, from the position analyzer domain, needed to open a filter channel.)

at the target location. Hence, the overall time to open a channel will be greater for the stimulus KRB than for |R|.

Therefore, the target–flanker similarity factor, C_i, represents the *remaining amount of information of processing* required to open the filter channel, given the initial rates of flow at the target and flanker locations (the information flow profile). The index i denotes a given ensemble of target and flankers.

The overall rate at which information flow at the target location in the filter map increases because of input from PA is assumed to depend on the gradient value at that location, $g(x)$. The gradient, $g(x)$, can thus be viewed as a distribution of rates of processing across locations in visual space. Thus, $g(x)$ is scaled in units of amount of information flow per unit time, and C_i is scaled in units of amount of information flow. The ratio $C_i/g(x)$ is therefore scaled in time units. Thus, when the target appears at the center location where the gradient value is highest, the PA input produces a channel opening sooner than when the target appears at locations away from center where the gradient value is lower.

Equation 1 produces V-shaped RT curves with arms that are virtually linear, providing that the sides of the gradient are approximated by a reasonably well-behaved function with first derivative positive on the left and negative on the right, and $s(x)$ is approximately linear. An example of a gradient together with three different levels of target–flanker similarity (e.g., |R|, VRY, KRB, corresponding to C_1, C_2, C_3, respectively) can be seen in Figure 4. Using this figure, one can derive in an informal manner a reaction-time curve for a particular target–flanker ensemble. First, one selects a location, x, and then divides the target–flanker value, C_i, by the value of the gradient at that location, $g(x)$. (One can do this by taking specific values from the curves in Figure 4.) The resulting RT curves for the three target–flanker similarities are shown in Figure 5. Using this informal graphic method, one can observe that the slope of the V curve increases with target–flanker similarity. Using the formal analytic method of first differentiating Equation 1 with respect to x, to obtain the slope equation, and then with respect to C_i, we observe that the slopes of the curves increase as C_i increases. When the eccentricity factor, $s(x)$, is taken into account, the predicted differences in slopes of the three reaction-time curves shown in Figure 5 must be increased somewhat further because $s(x)$ also interacts with C_i. Nevertheless, Figures 4 and 5 show how three examples of target–flanker similarities can generate three different reaction-time curves based on assumed interactions at the filter map among the inputs from three other domains: the input from a gradient in the LE domain, the profile of input rates across the locations of the target and flankers projected from the FR domain, and the input from the PA domain at the center location of the target.

The Moving-Spotlight Model of Attention Change

Currently, there is another view of how the selected area of attention changes, which may be called the moving-spotlight model (e.g., Posner, Walker, Friedrich, & Rafal, 1984; Remington & Pierce, 1984; Shulman, Remington, & McLean, 1979; Tsal, 1983). Recent critical reviews of current versions of the spotlight model are given by Eriksen and Murphy (1987) and by Yantis (1988). A moving-spotlight model describes attention as a focus or spotlight that moves about the visual field in a manner analogous to the way a real-world spotlight moves and illuminates objects in its path. The illumination provided by the attentional spotlight is assumed to represent the application of attentional resources needed to perform some perceptual–cognitive task. Certain tasks are able to be performed, it is assumed, only when the spotlight is positioned at the appropriate location.

The moving-spotlight notion can be said to follow the metaphor of the movement of the eye. When the eye moves across a stimulus display, the fovea acts as a region of specialized processing, analogous to the selected area of attention. During the movement of the eye, the fovea may sweep across the visual field, or it may make a saccadic jump. In both cases, the time taken to move the fovea to a new location is an increasing function of distance (Rayner, 1978). Similarly, when the area of selective attention shifts, it is assumed that something leaves one location and moves to another. We may also note that the eye metaphor carries with it the implication that there exists only one connected area of specialized foveal processing, so that one is easily led to infer that selective attention operates at only one location at a time, although in the case of the spotlight, the size of the spotlight may vary.

For the experiment discussed earlier (Table 1), it would be assumed that the warning signal guides the adjustment of the spotlight to the center location and width of the letter S that is expected to follow the warning signal. When the second target, |R|, appears away from center, the spotlight moves to the location of the |R| and is aligned on the R between the line flankers so that the R can be identified. The movement may be described as either analog or discrete for present purposes.

Formal Treatment of the Moving-Spotlight Model

If the spotlight shifts with a constant velocity, the RT to the |R| should be linearly related to the absolute distance of the

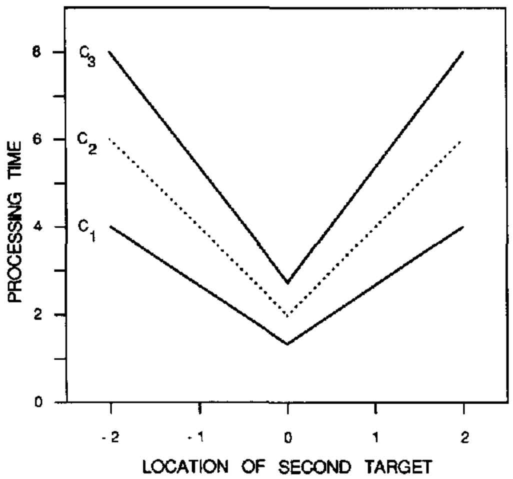

Figure 5. Theoretical reaction-time curves generated by the gradient and target–flanker similarity processing amounts shown in Figure 4 (omitting the effects of the eccentricity factor).

shift, $|x|$, divided by the velocity, v, that is, $|x|/v$ (we shall let the symbol x denote $|x|$ henceforth, to simplify notation). It can be seen that this relation generates the V curve shown at the top of Figure 2.

The appropriate equation for the moving-spotlight model then becomes

$$\mathrm{RT}(x) = x/v + C_i s(x)/f + T_r, \qquad (2)$$

where x denotes the distance (in either horizontal direction) of the target probe from the location of initial focus, v denotes velocity of the spotlight movement, C_i denotes the remaining amount of processing needed to filter the target given the ith level of target–flanker similarity, $s(x)$ denotes the eccentricity factor, f denotes the constant unit rate of processing within the spotlight area, and T_r denotes residual reaction time.

Equation 2 will generate a V curve of reaction time with linear arms. Differentiating Equation 2, first with respect to x to obtain the slope equation and then with respect to C_i, shows that the attention movement factor, $1/v$, drops out, so that the slope of an arm of the V curve depends on the interaction of C_i only with $s(x)$, the eccentricity factor. In contrast, Equation 1 of the gradient model indicates that the slope of a V-curve arm arises from the interaction of C_i with *both* $s(x)$ and $g(x)$.

Test of the Gradient Model Against the Moving-Spotlight Model

One way to induce the two models of attention change to generate contrasting predictions is to vary C, the target–flanker similarity, because C_i is additive with the movement factor, $1/v$ in the moving-spotlight model, and multiplicative with the gradient factor, $1/g(x)$, in the gradient model. Examples of flankers for R in increasing difficulty are the following: |R|, YRV, and KRB. Examples of flankers for another target, 7, are the following: |7|, C7U, and I7X. We expect filtering time to increase as the similarity between a given target and its flanker increases (Buoma, 1980; Eriksen & Eriksen, 1974; Estes, 1982).

Both the moving-spotlight and gradient equations predict that the slopes of the arms of the V curve will increase with C_i because the eccentricity factor, $s(x)$, interacts multiplicatively with C_i in both equations. However, the gradient equation predicts that the slopes will increase further with C_i because the gradient factor, $1/g(x)$, also interacts multiplicatively with C_i. The methodological problem is to find a way to hold constant the eccentricity factor while varying the attentional change factor (gradient or movement), so that we can determine whether this factor indeed interacts with C_i to produce a RT slope change, as the gradient theory predicts, or whether the change factor does not interact with C_i to produce a slope change, as the moving-spotlight theory predicts.

The way that the attentional change factor can be varied without changing the eccentricity factor is to vary the width of attention spread at the time that the second target probe appears, as shown in Tables 1 and 2 and in Figure 2. If one happened to be successful in spreading attention uniformly across all locations of the second target, the attentional change factor in both equations would be constant. That is, $g(x)$ would have one value for all x, and the term $1/v$ would drop out of the moving-spotlight equation because no attention movement would be necessary to locate and process the second target. Any obtained differences in slopes of the V curves of reaction time due to variations in C_i should reflect only interactions between C_i and the eccentricity factor, $s(x)$, alone. Then one could compare the slope differences obtained under the wide-attention condition, with the slope differences obtained under a narrow-attention condition (which would involve attention changes), and any observed change in slope differences between the two conditions could be interpreted as favoring the gradient model.

Even if attention were not uniformly spread across the locations of the second target, an appreciable difference in the amount of spread between the narrow and wide conditions will suffice as a basis for contrasting the predictions of the two theories. Specifically, the moving-spotlight theory predicts that the *differences* between RT slopes produced by varying C_i *will remain the same* across narrow and wide attention conditions because it predicts that $1/v$ adds with C_i. This prediction assumes that the movement factor in Equation 2, $1/v$, does not change with changes in C_i; that is, it assumes that the velocity of the spotlight movement is constant across all flanker conditions. In contrast, the gradient model predicts that differences between RT slopes due to changes in C_i *will increase* from the wide- to the narrow-attention conditions. This prediction derives from the assumption, expressed in Equation 1, that $1/g(x)$ multiplies C_i.

The Experiments

In Experiment 1, attention was concentrated narrowly to the letter S (first target) prior to the presentation of the R or 7 (second target). In Experiment 2, attention was spread widely to encompass the nine-letter word WHOLESALE (versus various misspellings of it). We refer to Experiment 1 as the *narrow experiment* and to Experiment 2 as the *wide experiment.*

Experiment 1

Method

Subjects. Subjects were 12 undergraduate students at the University of California, Irvine.

Apparatus and displays. A Cromemco Z80 microprocessor controlled the presentation of stimulus displays and the recording of response measures. Stimuli were presented as black figures on a white screen on a Setchell-Carlson monitor at a distance of approximately 530 mm. An adjustable chin and head rest was used to maintain this distance at all times. At this distance, a displayed character subtended a visual angle of approximately 0.27° horizontally and 0.65° vertically. The angle of a space between characters was approximately 0.16°. Thus, the center-to-center angle between adjacent characters was about 0.43°. Subjects were required to respond to the stimuli by pressing a button. A 28-cm × 36-cm response panel contained a 2.5-cm button for responses.

Stimuli. Each trial contained three successive displays, the warning signal, the first target, and the second target, following the scheme shown in Table 1. The warning signal and first target were both 11 characters long, and both were presented in the same location. The warning signal was a horizontal string of #s, with an asterisk in the center (i.e., #####*#####). The first target was a horizontal string of alternating 5s and 8s with either an S, or a 5 or an 8 in the center (e.g., 58585S85858 or 85858558585). Subjects were asked to identify the S at the center of the first target. The identification of the S ensured that subjects would have to attend to the center location. The purpose of the warning signal was to give subjects the opportunity to build up concentration at the center location in the period of time just prior to the first target onset.

The second target was presented immediately after the first target. This target required subjects to identify a letter (or digit) surrounded by various types of flankers. The target could appear in one of five equally spaced locations within the horizontal range defined by the two warning signals. The target appeared either exactly at the center of the range, that is, in the same location as the asterisk and the S, or two or four spaces to the left or right of center (corresponding to a distance of 0.9° or 1.8° from the center). In an attempt to obtain somewhat greater generality of the results, two different characters were used as the second targets: R (to be identified against P and Q) and 7 (to be identified against Z and T). The four main conditions of the experiment were defined by the type of flanker placed to the left and right of the target character. It was assumed that greater similarity of flankers implied greater difficulty of processing the targets. In the no-flanker condition (serving as a control), the targets had no flankers. In the line-flanker condition, target characters were flanked with vertical lines (e.g., |R|) at a distance of 0.16°). For the neutral flanker condition, V and Y were flankers for the R, and C and U were flankers for the 7. The conflicting flanker condition had B and K as flankers to the R, and I and X as flankers to the 7. In both the neutral and conflicting flanker conditions, there were two possible combinations of target and flanker (e.g., VRY or YRV); each target–flanker combination was presented an equal number of times.

Procedure. Each trial began with the presentation of the warning signal for 750 ms. Next, the first target was displayed in the same location as the warning signal for 150 ms. The first target was then replaced by the second target, which appeared for 217 ms. The subjects were given 1,000 ms following the onset of the target to respond before an error message was displayed.

Subjects were instructed to respond with a button press only when the first target contained the letter S and the second target was an R (or a 7, depending on the condition being run). Subjects were told that the letter S in the first target would appear only in the center location, whereas the second target might appear in any of five locations.

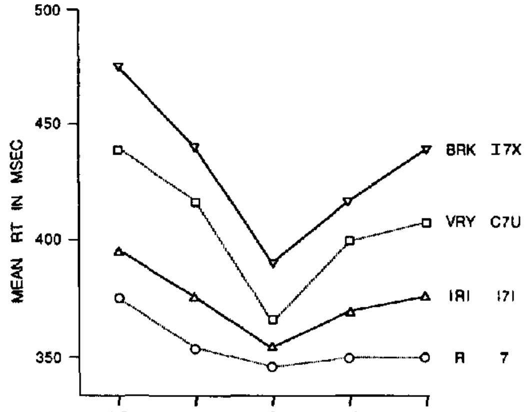

Figure 6. Experiment 1 (the narrow experiment). (Mean reaction times to the second target, R [or 7], as a function of its location and type of flanker when a single letter, S, was the first target. Flanker condition was varied across days; data are from 12 subjects.)

Errors were indicated by the display ERROR immediately following an incorrect button press. Misses were indicated by the same message 1,000 ms after the onset of the target. The duration of the error message was 500 ms. The intertrial interval was a blank screen for 750 ms following a button press or the offset of the error message.

Subjects were run individually in a normally lighted room. Each subject ran four sessions, corresponding to each of the four flanker conditions, and ran each session on a different day. The order of running the four flanker conditions was balanced across the 12 subjects using three different Latin squares. Each session contained two practice blocks and two test blocks; subjects ran one practice block followed by one test block with one target character (either R or 7) and then one practice block and one test block with the other target character. One half the subjects began their first session with the R condition and half with the 7 condition.

Each block contained four types of trials, corresponding to the possible combinations of first and second targets. (The warning signal was the same for all trials.) On one half the trials, the first target contained an S in the center and the second target was an R (or a 7). This was the only trial type on which subjects were to respond. For one quarter of the trials, the first target contained an S, but the second target was a catch (either P or Q, or T or Z). On the remaining one fourth of the trials, the first target contained no S. One half of these (⅛ of the total) had response second targets (R or 7), and the other half had catch second targets. A practice block consisted of 48 trials and a test block of 160 trials.

Results

The mean reaction times to the second targets (R and 7 combined) for the four flanker conditions over the five locations are given in Figure 6. Each point is based on approximately 32 observations per subject for a total of approximately 384 observations.

An analysis of variance was used to compare the reaction times to the second target over the factors of flanker condition, target character, and target location. The main effect of location was significant, $F(4, 44) = 60.1, p < .01$, indicating a reaction-time increase with distance from the center location. The main effect of flanker was also significant, $F(3, 33) = 65.5$, $p < .01$, indicating that reaction time increases with flanker difficulty. The effect of target character was not significant, $F(1, 11) = 2.00$, $p = .97$. The Flanker × Location interaction was significant, $F(12, 132) = 6.11$, $p < .01$, indicating that the slopes of the reaction-time curves diverge with flanker difficulty. No other interactions were significant.

The rates of misses were 4%, 5%, 2%, and 6% for the no-flanker, line-flanker, neutral-flanker, and conflicting-flanker conditions, respectively. The rates of errors were 7%, 7%, 8%, and 8%, respectively. Almost all of the errors were made on trials in which the first target contained an S; that is, nearly all of the errors were made in identifying the second target.

Discussion

The slopes of the reaction-time curves increase with flanker difficulty and approximately double in value from the vertical-line flanker conditions (|R| and |7|) to the shared-feature flanker conditions (BRK and I7X). However, the obtained increase in slopes in Figure 6 cannot be evaluated as an indicator of an attention factor (i.e., a gradient) until the contribution of the eccentricity factor is assessed. That is, one could claim that increased similarity of flankers to the target could interact more strongly with sensitivity characteristics of the visual system and thereby produce the increases in reaction-time slopes shown in Figure 6.

We attempted in Experiment 2 to widen the concentration of attention across the entire range of target locations (approximately 3.6°) by presenting a nine-letter word to be identified. If attention were distributed homogeneously across the range of targets, then obtained differences in reaction-time slopes should be attributable to the eccentricity factor. The word we used to induce a wide concentration of attention was the word WHOLESALE, which was chosen because it is a familiar word that shares none of the letters with the sets of targets and flankers of Experiment 1. Subjects were first given a warning signal (### ######### ###) followed by the word WHOLESALE 75% of the time, and a probe 25% of the time (the catch stimuli for WHOLESALE were SHOLESALE, WHALESALE, WHOLASALE, WHOLESELE, and WHOLESALA). In a previous study (LaBerge, 1983), this procedure, which may be termed the *probe-instead* procedure, involved two instead of three events on a trial. The main virtue of this procedure over the *probe-after* procedure (described here in Table 1) for present purposes is that subjects are presumed to set the width of attention to correspond to the size of the word at the moment they expect the word to appear, instead of maintaining the width throughout the display of the first target. Occasionally, instead of the word, they were shown the probe target. Thus, the probe target appeared at the moment that attention is spread widely in anticipation of the nine-letter word.

Experiment 2

Method

Subjects. A total of 8 undergraduate and graduate students at the University of California, Irvine, served as paid subjects.

Apparatus and displays. An IBM AT computer presented white characters on a dark screen of a NEC monitor and recorded response measures. Other features of the apparatus were the same as described for Experiment 1.

Stimuli. Each trial contained two successive displays: the warning signal and either a word target or one of the target–flanker stimuli described in Experiment 1. The warning signal was a horizontal string of 15 #s (### ######### ###) with two spaces inserted to make salient the central nine #s. The word target that replaced the warning signal was the word WHOLESALE (which shares none of its letters with the probe targets and flankers). The catch stimuli were SHOLESALE, WHALESALE, WHOLASALE, WHOLESELE, and WHOLESALA. The probe targets were the same as the Target 2 stimuli described in Experiment 1. A block of trials contained only one of the four types of flanker conditions and one type of target (either R or 7).

Procedure. A trial began with a warning signal presented for 750 ms. It was replaced by either the string of nine letters (75% of the time) or by a probe (25% of the time) at a duration of 217 ms. The subjects were allowed 1,000 ms following the onset of the target to respond before the message MISSED was displayed.

The subjects were instructed to respond either to the word WHOLESALE or to an R (or 7). Error messages and their durations were the same as in Experiment 1. The intertrial interval showed a blank screen for 750 ms following a button press or following the 1,000-ms waiting period.

The subjects were run individually in a normally lighted room. Each subject ran five sessions on 5 different days. The first day's session provided practice with the word WHOLESALE and its catch stimuli. In that practice block, a given probe (R vs. P or Q, or 7 vs. T or Z) was presented with all four of its flanker conditions within a practice block. Then a second practice block presented the other probe target with its flankers along with the target word. In the remaining 4 days, only one flanker type was displayed on each day. Two ½-hr sessions, each containing two test blocks, were run per day, and in one block the probe target was R (vs. P or Q) and in the other block the probe target was 7 (vs. T or Z). The order of target type was balanced against other conditions of the experiment. The order of the flanker type across the 4 days was balanced across the 8 subjects by two different 4 × 4 Latin squares.

Each day's session contained two test blocks of 160 trials each. The word WHOLESALE appeared on 60 trials of a block, and the five misspellings of that word each appeared 12 times, making a total of 120 trials, or 75% of the total of 160 trials. On the remaining 25% of the trials, the probe target R (or 7) appeared 20 times, 4 times in each of the five locations corresponding to the WHOLESALE letter positions of 1, 3, 5, 7, and 9. The catch probe stimuli P and Q (or T and Z) each appeared twice in each of the five locations. A practice block was given before the first test block on a day, and contained 40 trials distributed among the various targets and catch stimuli in the same proportions as in the test blocks.

Results

The mean reaction times at each target position for each flanker type are given in Figure 7. Each point is based on approximately 16 observations per subject, for a total of approximately 128 observations. An analysis of variance compared reaction times over the factors of flanker type, target character, and target location. The main effect of location was significant, $F(7, 28) = 7.85$, $p < .01$, indicating that the reaction-time curves are indeed not constant over location. The significant effect of flanker type, $F(3, 21) = 10.6$, $p < .01$, indicates that reaction time differs between the flanker conditions. The effect

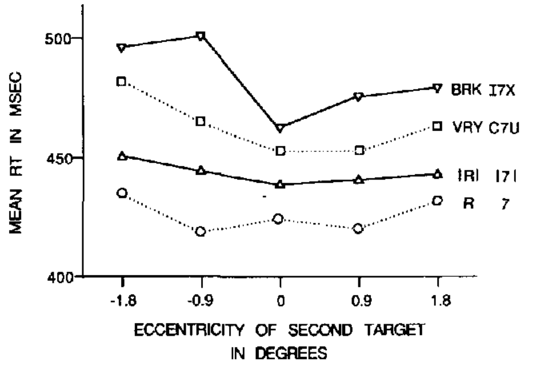

Figure 7. Experiment 2 (the wide experiment). (Mean reaction times to the probe target, R [or 7], as a function of its location and type of flanker, given that subjects were instructed to identify a nine-letter word that appeared on 75% of the trials. Flanker condition was varied across days; data are from 8 subjects.)

of target type was not significant, $F(1, 7) = 1.45$, $p = .27$. The interaction of flanker with location was significant, $F(12, 84) = 3.28$, $p < .01$, indicating differences in slopes of the reaction-time curves for the different flanker conditions. The Target × Location interaction was also significant, $F(4, 28) = 3.22$, $p < .05$.

The rates of errors were 1.0%, 1.5%, 7.0%, and 11.0% for the no-flanker, line-flanker, neutral-flanker, and conflicting-flanker conditions, respectively. The rates of misses were 0.3%, 0.5%, 1.0%, and 4.0%, respectively.

Discussion

The curves of Figure 7 show nonzero slopes, and the slopes clearly increase with flanker type and in the same order as they increase in Figure 6. We note that the targets with the vertical-line flankers exhibit very small slopes, particularly on the right side, indicating a very small interaction of eccentricity with this type of flanker. This finding accords well with the curve shown in the lower half of Figure 2, and with the results of a previous study (LaBerge & Brown, 1986) that showed negligible evidence of eccentricity effects over the same range, using the same vertical-line flankers on the target letter O. Presumably, vertical-line flankers are sufficiently dissimilar to the targets used in these studies that the interaction of the target–flanker similarity factor with the eccentricity factor was negligible over the range of second target locations. The other flankers, however, do show substantial interactions with eccentricity. However, it is noteworthy that the slopes of the highest V curve (BRK and I7X) in Figure 7 are less than the slopes of the lowest flankered curve (|R| and |7|) of Figure 6.

For purposes of comparing the predictions of the gradient and moving-spotlight models of attention, the curves of interest are the upper three curves of Figures 6 and 7. The lowest curves in Figures 6 and 7 are considered outside the predictive range of the models because at least a part of the data making up these curves could arise from processes that bypass the attentional filter. When the familiar target R (or 7) is presented without distracting items near it, the filter is not needed to select feature information flowing from the FR domain to the SI domain, and therefore the resulting reaction-time curve may not reflect the operation of attention factors, be they velocity or gradient in nature.

The gradient model predicts that the differences between the slopes of the three upper curves of Figure 6 (Experiment 1) should be greater than the corresponding differences in Figure 7 (Experiment 2), whereas the moving-spotlight model predicts no such differences. An examination of Figures 6 and 7, the values of Table 3, and the overall positive values in Table 4 support the gradient model. An analysis of variance of the combined data of Experiments 1 and 2 showed that the three-way interaction of Experiment × Flanker × Position was significant, $F(12, 216) = 2.01$, $p < .05$, indicating a significant difference in the differences between slopes of the corresponding reaction-time curves in each experiment.

One might attempt to salvage the moving-spotlight account of the present data by permitting the velocity, v, to change with flanker type, so that the predicted differences between slopes in the narrow experiment would be increased beyond the differences expected from the interaction of flanker type and the eccentricity factor. That is, the curves of the more similar target–flanker ensembles (e.g., BRK and I7X) would be incremented by the $1/v$ movement factor more than a less similar flanker–target ensemble (e.g., |R| and |7|), making v a decreasing function of target–flanker similarity, C_i. However, it seems intuitively difficult to justify the claim that the more difficult flankers produce the slower velocities. It is assumed that the spotlight is required for the identification of the target, that is, that the processing needed to do the identification takes place only after the spotlight has reached the target location. But if the type of flanker is to have some effect on the velocity of the spotlight, then most, if not all, of the features of the target character and its flankers must have been processed before the spotlight arrives. Moreover, if the more similar target–flanker ensembles require longer processing times to identify the target, then, given limited exposure time, optimally, one would attempt to move attention more rapidly to the location of more similar target–flanker ensembles, not less rapidly, as the ordering of slopes in Figure 6 indicates.

Furthermore, the velocity factor requires large adjustments to fit the reaction-time data of the narrow experiment (by more than a factor of 2 on each side). The requirement that velocity be changed to account for the data reduces considerably the explanatory economy of the velocity assumption, and therefore the moving-spotlight model, as represented by Equation 2, does not efficiently account for the data of the present experiments.

Although it seems nonadaptive for a moving-spotlight mechanism to reduce movement velocity for the more similar target–flankers ensembles, there still remains the possibility, however remote, that the velocity of the spotlight could be set in advance of a trial in Experiments 1 and 2 because flanker conditions were varied between blocks. It would seem that this hypothesis could be tested simply by varying flanker conditions within blocks. That is, if subjects had no foreknowledge of which flanker condition would occur on a given trial, then they would not be able to set the velocity of the spotlight movement appro-

Table 3
Slopes of Reaction-Time Curves of Experiments 1 and 2

	Experiment 1 (narrow)		Experiment 2 (wide)	
Flanker condition	Left side	Right side	Left side	Right side
Fl$_3$	42.0	22.5	15.0	8.0
	(6.5)	(3.5)	(2.0)	(3.0)
Fl$_2$	35.5	19.0	13.0	5.0
	(14.5)	(10.5)	(7.5)	(3.0)
Fl$_1$	21.0	9.5	5.5	2.0

Note. Slope differences are given in parentheses. Slopes were computed by least squares fit to reaction-time points.

priate to a target–flanker ensemble before it was displayed. A third experiment was therefore designed to vary target–flanker similarity conditions *within* blocks of trials.

Experiment 3 presented the three conditions (that had flankers) in Experiments 1 and 2, and required subjects to run in both the narrow- and wide-attention conditions. The critical test for the validity of a moving-spotlight model with variable velocity again will be the differences between reaction-time slopes for the curves of the three flanker conditions compared across the narrow- and wide-attention conditions. The moving-spotlight model predicts no difference between the slope differences across wide and narrow conditions.

Experiment 3

Method

Subjects. There were 20 paid subjects in Experiment 3.

Apparatus and displays. The equipment and display specifications were identical to those for Experiment 2.

Stimuli. Each trial contained two displays. The warning signal indicated the location and width of the expected target. For the narrow condition, the warning signal was an asterisk surrounded by #s (####*####) as in Experiment 1, and for the wide condition, the warning signal was a string of three groups of #s (### ######### ###) as in Experiment 2. The expected target appeared 75% of the time following the warning signal. In the narrow condition, the expected target was an S surrounded by 5s and 8s; the catch target replaced the S with either a 5 or an 8. In the wide condition, the expected target was the word WHOLESALE with the same catch targets as in Experiment 2. In both conditions, the probe targets appeared 25% of the time. There were two probe targets (R vs. P, Q and 7 vs. T, Z) and three flanker conditions (|R|, |7|; VRY, C7D; and BRK, I7X). The probe targets appeared in one of five locations: at the center of the display, or two versus four spaces to the left or right of center.

Table 4
Differences Between Slope Differences in Experiments 1 and 2

	(Narrow − Wide)	
Flanker differences	Left side	Right side
Fl$_3$ − Fl$_2$	4.5	0.5
Fl$_2$ − Fl$_1$	7.0	7.5

Procedure. The task for the subject was to respond with a button press to the letter S or R (or 7) in the narrow condition. In the wide condition, the letter S was replaced by the word WHOLESALE. The subjects ran 10 sessions, 2 per day, for 5 days. The first day's 2 sessions consisted of practice blocks that presented each of the four target types (58585S85858, WHOLESALE, R, 7), separately. The remaining 8 sessions presented four combinations of expected target and probe target: S and R, S and 7 (the narrow conditions), WHOLESALE and R, and WHOLESALE and 7 (the wide conditions). Each subject ran only the wide or narrow condition on any given day, one session with the R probe target and one session with the 7 probe target. Each session began with a practice block of 40 trials containing only the expected target (S or WHOLESALE) and its catches. The test block in each session contained 360 trials, with a rest every 60 trials. Each trial consisted of two consecutive displays (described under Stimuli), the warning signal and the target. The warning signal was presented for 1,000 ms. The expected target, S, was presented for 133 ms and WHOLESALE was presented for 200 ms. The probe target (R or 7) was presented for 217 ms. The expected target appeared on 270 trials (75% of the time), of which one half (135) were catch trials. The remaining 90 trials (25%) contained the probe target. Because there were three flanker conditions, each flanker condition appeared on 30 trials (15 response trials and 15 catch trials). Thus, each probe target requiring a response appeared three times during a block in each of the five locations. Once the target (either expected or probe) appeared, subjects were given 800 ms to respond, after which time the message MISSED appeared on the screen. Errors were indicated by the

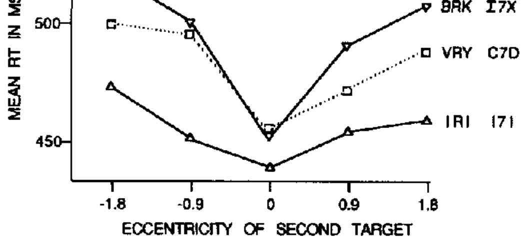

Figure 8. Experiment 3 (narrow condition). (Mean reaction times to the probe target, R [or 7], as a function of its location and type of flanker given that subjects were instructed to identify a single letter, S, that appeared on 75% of the trials. Flanker condition was varied within blocks; data are from 20 subjects.)

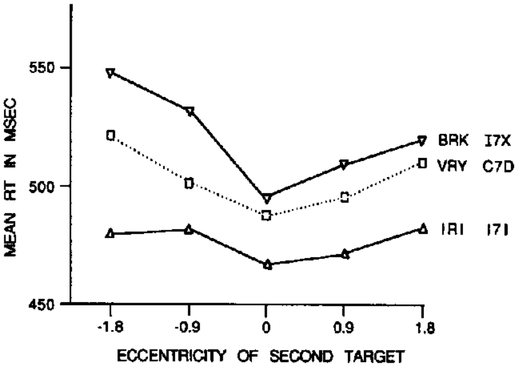

Figure 9. Experiment 3 (wide condition). (Mean reaction times to the probe target, R [or 7], as a function of its location and type of flanker, given that subjects were instructed to identify a nine-letter word that appeared on 75% of the trials. Flanker condition was varied within blocks; data are from 20 subjects.)

message ERROR. The intertrial interval was 750 ms. Each subject ran 2 days (2 sessions per day) on the wide condition and 2 days (2 sessions per day) on the narrow condition.

Results

The mean reaction times for the narrow and wide conditions of Experiment 3 are shown in Figures 8 and 9, respectively. Each point of these graphs is based on approximately 240 observations. An analysis of variance was used to compare the reaction times over the factors of condition (narrow or wide), target (R or 7), flanker type, target location, and order of running. The effect of location was significant, $F(11, 64) = 46.5$, $p < .01$, indicating that the reaction-time curves have a V shape. The effect of flanker was significant, $F(1, 16) = 23.4$, $p < .01$, indicating overall differences in reaction time as a function of flanker type. The effects of condition and target type were also significant, $F(1, 16) = 23.4$, $p < .01$, and $F(1, 16) = 8.14$, $p < .05$, respectively. Both the Flanker × Location and the Condition × Location interactions were significant, $F(8, 128) = 3.56$, $p < .01$, and $F(4, 64) = 4.64$, $p < .01$, indicating that the reaction-time slopes diverge with flanker type and that the slopes are flatter for the wide condition. The Target × Flanker interaction was significant, $F(2, 32) = 3.32$, $p < .05$. Finally, the Condition × Flanker × Location interaction was significant, $F(8, 128) = 2.56$, $p < .05$, indicating that the differences between the slopes of the reaction-time curves for the three flanker types were greater overall in the narrow condition than in the wide condition (cf. Tables 5 and 6).

For the wide condition, the percentage errors were 1.0, 2.6, and 7.8 for the line, neutral, and conflicting flankers, respectively; the percentage misses were 1.0, 1.3, and 3.9, respectively. For the narrow condition, the percentage errors were 2.3, 6.2, and 11.7 for the line, neutral, and conflicting flankers, respectively; the percentage misses were 1.0, 1.3, and 4.4, respectively.

Discussion

The result of most importance for comparing the moving-spotlight and gradient models is the overall significant difference of the reaction-time slope differences between the wide and narrow conditions. The statistical support for the difference between the differences in Experiment 3 implies that a single velocity moving-spotlight model cannot account for the different slopes of the narrow condition.

Thus, to account for the data of both wide and narrow attention conditions of Experiment 3, the moving-spotlight model must apparently assume, as it did in the case of the data of Experiments 1 and 2, that velocity changes with flanker type, and possibly also with side of target location. But in Experiment 3, in which subjects could not know in advance what flanker condition would appear on a trial, the appropriate setting of velocity appropriate to each flanker condition could almost surely not be made from higher order processes of the subject. However, it is conceivable that the velocity setting could be made very early in processing within a trial, for example, from some computation made on the initial registration of the target–flanker ensemble in the FR domain. For example, the relatively equal information flow across the stimulus BRK (due to high target–flanker similarity) might signal the filter channel to move slowly, whereas the more unequal distribution of flow across the stimulus |R| might signal the filter channel to move quickly. Such an account seems rather strained because it is not clear how to specify the implied connections between such early processing and the movement of a channel.

In summary, the simple gradient model of location expectation generates a family of V curves of reaction time in these experimental tasks that appear to give a good account of the data from a variety of flanker conditions. The moving-spotlight model, in contrast, cannot account for the same data without assuming a variable velocity of spotlight movement, and in the procedure of Experiment 3, it appears that subjects have no plausible opportunity to adjust the velocity prior to the onset of a display.

An incidental finding in Experiment 3 is that the overall level of reaction time for the wide condition is greater than that for the narrow condition, which is the reverse of the finding shown in Figure 2. An experiment by Egeth (1977) also found longer reaction times for a condition in which attention was spread widely as opposed to being spread narrowly. The extent of spread in his experiment was 3.8°, which is close to the 3.6° spread in the present Experiment 3, and contrasts with the 2° spread underlying the data shown in Figure 2, and the 2° of spread underlying the data of an earlier experiment by LaBerge (1983). Thus, one salient difference between experiments that show longer reaction times for wide versus narrow spreads of attention is the extent of the spread. Further study is needed to explore this relation and to assess its theoretical implications.

Another incidental result, found in all three experiments, is an asymmetry between the slopes of the two arms of the reaction-time curves. A similar asymmetry in V-curve slopes was found in previous studies (LaBerge, 1983, LaBerge & Brown, 1986). Downing and Pinker (1985) noted a left–right asymmetry in attentional costs for a luminance detection task: Left-visual field costs were found to be greater than right-visual field costs. Hughes and Zimba (1985) also found a right-hemifield superiority effect for reaction times to a luminance onset. If one were to use Equation 1 to fit predicted curves to the data of

Table 5
Slopes of Reaction-Time Curves of Experiment 3

	Narrow condition		Wide condition	
Flanker condition	Left side	Right side	Left side	Right side
Fl$_3$	33.5	27.5	26.5	12.5
	(12.0)	(12.0)	(9.5)	(1.5)
Fl$_2$	21.5	15.5	17.0	11.0
	(5.0)	(6.5)	(9.5)	(2.5)
Fl$_1$	16.5	9.0	7.5	8.5

Note. Slope differences are given in parentheses. Slopes were computed by least squares fit to reaction-time points.

Figures 6, 7, 8, and 9, one can assume an asymmetry either in g(x), s(x), or both, such that the values of these functions are higher for positive x than for negative x. It is conceivable that an asymmetry in g(x) could represent a right-side bias in reading routines on the part of the subjects, who were all native readers of English. Such a hypothesis could be tested with subjects who read language right-to-left. A sufficiently large asymmetry in eccentricity factor, s(x), necessary to account for the obtained slope differences has not, to our knowledge, been demonstrated in acuity studies that use accuracy measures. This factor should be tested using reaction-time measures, with appropriate controls for gradient effects. A clear resolution of this issue waits upon further experimentation.

General Discussion

It appears that a gradient model offers a more parsimonious account of the data of the present experiments than a moving-spotlight model, because the gradient model predicts the change in slopes of the three flanker types on the basis of a single gradient, whereas the moving-spotlight theory predicts the change in slopes only by adjusting the velocity parameter for each type of flanker.

If the constant velocity moving-spotlight model were combined with a gradient model such that the spotlight had a "skirt" or "fringe," could it account for the results of the present three experiments, even though it would be less parsimonious an account than that given by the simple gradient model? The account given by a moving-gradient or spotlight-with-a-fringe model can be described by referring to Figure 4, in which the gradient's "spotlight" could be represented as the flat sector in the center and its fringe by the two curves that decrease on each side of the center sector. When a target item is displayed at the far-right position, for example, the gradient begins to shift toward that location and stops when the center sector reaches the target's location. The prediction of changing slope values of reaction time is derived from the following considerations. Let t_1 denote the time of onset of the (second) target, that is, the time when the location of the gradient is in the center; let t_2 denote the time when the location of the gradient is half way between center and the target location; and let t_3 denote the time when the gradient reaches the target. The amount of attentional activation, g(x), *at the target location* increases across times t_1, t_2, and t_3, as the tail of the gradient moves higher at that location. The average of these three values of g(x) across time can be regarded as equivalent to the g(x) value of a stationary gradient, which is the type of gradient on which the simple gradient model is based. Therefore, the moving-gradient model, or moving-spotlight-with-a-fringe model would seem to be able to generate the same predictions as the stationary gradient model. Such a model would have to specify the degree of spread of its fringe or gradient, as well as the velocity of movement, because the amount of slope change predicted varies directly with the amount of gradient spread.

Table 6
Differences Between Slope Differences in Experiment 3

	(Narrow − Wide)	
Flanker differences	Left side	Right side
Fl$_3$ − Fl$_2$	2.5	10.5
Fl$_2$ − Fl$_1$	−4.5	4.0

However, if the moving-gradient model is to be a serious contender it must also be able to account for the requirements of filtering. One way that the filtering process could be integrated with the moving-gradient model is to assume that the gradient itself can filter out the flankers from the target by virtue of the higher level of information flow at the center sector of the gradient. But to do this, the center sector of the gradient would have to be as small as the width of the second target in order to produce a higher level of flow at the center target location as compared with the level of flow at the flanker locations to open a filter channel. Moreover, to begin such filtering, the gradient would have to be positioned at the target location, regardless of which location in visual space the target appears. Thus, no appreciable progress in filtering can occur during the movement of the gradient. This version of the moving-gradient model would therefore make the same predictions concerning slope changes in the three present experiments as the moving-spotlight model. Because the stationary-gradient model has already been favored over the moving-spotlight model, the stationary-gradient model is favored over this moving-gradient model as well.

The concept of a nonmobile gradient does not preclude the possibility that a gradient can be developed in a new location. We treat the case of forming new gradients later under the heading of precuing of locations. It is assumed that, given enough time, a gradient can be formed in a new location while the old gradient disappears. If the second target (e.g., in Table 1) were displayed away from center for a sufficient period of time, we expect that a second gradient would begin to be formed at the location of the second target, whereas the initial gradient at the center location begins to decline. Thus, on the present theory, the appearance of a new gradient clearly does not come about by a movement of the old gradient to the location of the new gradient. Perhaps the term *dynamic gradient* would be a more appropriate description than the term *stationary gradient*, but then it should be emphasized that a dynamic gradient does not move across the visual field in an analog or discrete manner.

Two Applications of the Theory

We now attempt to apply the theory to the cuing of locations away from the center of the visual field, and to the issue of automatic versus attentional processing of words.

Precuing of the Spatial Location of Attention

A considerable number of studies have shown that the reaction time for identifying or detecting a target can be reduced by precuing its spatial location, particularly when the precued location is away from the center of the eye. Eriksen and Hoffman (1973) and Hoffman (1975) displayed a single letter in one of several locations in a circular path surrounding a central fixation point. They precued the target location by presenting a marker slightly eccentric to the location of the target and found that reaction time was reduced 30–40 ms when the marker preceded the targets by a stimulus onset asynchrony (SOA) of 50–100 ms. Jonides (1981) obtained comparable results with a similar procedure. Posner and his colleagues (Posner & Cohen, 1984; Posner et al., 1980; Posner et al., 1984) precued one of a set of locations along a horizontal line by brightening a square in which the target would appear. In a typical condition, the precue was valid for a target display occurring at that position 80% of the time, and invalid for the other 20% of the time in which one of the other locations displayed the target. Reaction times to the target were faster in the valid location than in the nonvalid locations. Shulman et al. (1979) and Remington and Pierce (1984) used similar procedures with comparable findings. Tsal (1983) precued locations with a variable time period between cue onset and target display and found that reaction time decreased as the time between the cue and the target increased. In particular, the reaction time–SOA asymptote increased linearly with eccentricity.

Note that many of the tasks in the precuing literature do not require identification of a shape, but merely the detection of the luminous onset of an object. If we were to assume that the gradient operates only through the filter and that detection bypasses the filter, then the obtained reaction-time curves should show zero slopes. Although in such cases the filter is not required for a correct response, nevertheless, a subject may align the filter channel at the location of the object prior to the response. We believe that this apparently redundant processing comes from the subject's highly developed routine to index the position of an object as well as to determine its identity, and that obtaining location information typically requires the alignment of the filter.

Furthermore, subjects may be more likely to use the filter for unflankered targets when they have recently identified the same target with flankers present, as is the case for the designs of the present Experiments 1 and 2, and for Experiment 3 of the LaBerge and Brown (1986) study, in which subjects had only to detect the presence or absence of an asterisk. Also, subjects develop a habitual routine for examining the parts of an object following its identification as a whole, and examination of parts requires the operation of the filter. For example, when reading a familiar word, we apparently first process it as a whole, and occasionally then inspect its familiar letter components (e.g., Healy, Oliver, & McNamara, 1987; Johnson, 1975; LaBerge & Lawry, in press; Marmarik, 1977; O'Hara, 1980), perhaps to check for misspellings. Once the filter becomes involved in the processing of a part, a channel opens in the filter at a given location according to the constraints of an existing gradient. Therefore, on the trials in which subjects attend to the location of an object prior to responding, the reaction times to different target locations should show differences corresponding to the shape of the gradient. The higher the proportion of filter-involved trials within a block of trials, the more the slope of the mean reaction-time curve will be determined by the shape of the existing gradient.

Another way that the detection of a luminance onset of an object might be influenced by the gradient in the LE domain to produce a nonzero reaction-time slope is to assume that the gradient passes activation directly to the FR domain, as shown by the two-way arrows in Figure 3. Precuing a location on one side of the visual field should raise the activation levels on that side and, consequently, produce faster detections. We will describe evidence from recent event-related potential studies related to this issue in the last section of this article.

A typical interpretation of the operation of attention in precuing studies is that precuing a location induces an attentional focus, or spotlight, to move toward the target location so that when the target appears and is identified, the reaction time value will be less by the amount of time involved in the head start of the attention movement. When the precue duration is long enough so that the movement of the spotlight is complete prior to target onset, then further cue duration should not produce further savings in reaction time. Thus, this interpretation assumes that precuing affects arrival time of the focus.

The present theory proposes a somewhat different interpretation of the processes involved when spatial location of a target is precued. During the display of a warning signal, a gradient peak is presumed to be gradually established at a point centered on the warning signal's location, and of a size that is determined jointly by the area cued by the warning signal (especially when the boundaries of the area produce sharp changes in luminance, such as those produced by a single plus sign or dot), and the range in which subsequent targets are expected (LaBerge & Brown, 1986). When a precue marker appears, or a square abruptly changes its luminance, a channel opens at that location, as the channel at the initial fixation point closes. At the location of the open channel a new gradient begins to form, which builds to an asymptotic level at this location if enough time is allowed. Then, when the target appears and its representation in the FR domain is sent to the filter map, the information flow at the target location combines with the new gradient value at that location to open the filter channel. The processing of the target at the cued location will proceed faster the higher the peak of the developing gradient. Therefore, reaction time to a target will decrease as the SOA or precue duration increases, because the gradient is thereby given more time to develop to higher values at the new cued location.

To establish a relatively high gradient peak at a location away from retinal center may be more difficult in practice than to form the high, sharp peak that has presumably been established at the retinal center in the present experiments. In the narrow-attention experiment reported here, the subjects were given 1,000 ms during the warning signal to build the expectation for the location of the first target, S. During that time, it would seem that the position analyzer had to maintain input continuously at the location of the asterisk as the expectation grew to a high level. To maintain continuous PA input to a location away from center for comparable durations of time may be difficult for the system to achieve, even with trained subjects.

In summary, the present theory accounts for the advantage of location precuing on reaction time by assuming that what the precue does is to provide time for a gradient to develop, not time for a channel to move. The theory does not assume a mechanism for movement of the channel, in either the analogue or discrete sense. Instead, the selected area of attention, represented by the filter channel, emerges wherever there is sufficient differential in the information flow across locations in the filter map.

Attentional and Automatic Processing of Words

The assumptions concerning the operation of the filter in the present theory may clarify the way that attention is involved in the identification of words. One might assume that familiar words would be processed without attention (i.e., automatically) if their parts have been reorganized into a single unit (LaBerge, 1976; LaBerge & Samuels, 1974). However, the present theory makes an additional assumption, that is, that when a shape such as a word is displayed with other shapes in its neighborhood, the attentional filter must be involved in the identification process. Specifically, the filter must control the delivery to the SI domain of just the features from the location of the target word. To accomplish this, the channel must be aligned with the boundaries of the target word. So long as the channel encompasses locations of items in addition to locations of the features of the target, the SI domain will not identify the ensemble, regardless of the familiarity of the target and its consequent potential for automatic processing. For example, without appropriate channel positionings, the possibility of automatic processing of familiar words is blocked in the following display: Wor dsne edspa ces. Therefore, the potential for automatic processing of a shape presented in cluttered displays is revealed *after* the channel is positioned so that distracting items are filtered out.

In view of these considerations, one could say that a familiar word is processed automatically if the filter channel need not be narrowed to the parts of that word to produce an identification in the SI domain. For example, to identify the word THERE does not require that the filter be narrowed below a width of five spaces, because the whole shape THERE is familiar (i.e., it is stored as a strong unit in the SI domain). On the other hand, to identify unfamiliar words requires the narrowing of the filter to familiar components: spelling patterns (e.g., PHALANGER), or component words (e.g., HOVERCRAFT), or letters (e.g., KYZYL; LaBerge & Lawry, in press; Lawry & LaBerge, 1981). If a word can be identified on the basis of spelling patterns or component words, then the filter channel need not be narrowed down to a letter size, and the number of successive positionings of the filter will be less than it would be if each letter needed to be identified. Hence, identifying a word by parts larger than a letter could be described as using some automatic components not used in identifying a word letter-by-letter. This analysis could be extended to more minute operations of the filter if the letters themselves were unfamiliar and required successive identifications of their component line features to identify the word. Thus, an object, such as a word, contains a nested hierarchy of smaller shapes as its parts, and that object is processed more or less automatically, depending on the size of the components that SI is capable of identifying, and consequently on how much filtering is required for identification of the whole object to take place.

Therefore, we propose that a visual shape, such as a word, be characterized as capable of automatic processing when it can be identified under either of two related criteria: (a) The filter channel is aligned to the outline of the shape, or (b) the filter is not involved in the process of identification at all; that is, the information flows from the FR domain to the SI domain without selective modulation by the filter outputs. The first criterion of automaticity is applied more often because shapes are more frequently identified in the presence of other items. The second criterion of automaticity is applied less frequently because it requires that the familiar shape be presented in an otherwise empty field, which is a relatively rare event outside the laboratory.

The claim that the identification of a word presented in the context of other items (e.g., in the typical context of other words in written text) is not completely automatic because it involves attention is quite consistent with the assumptions of the present theory. The critical point is indicated by the term *completely automatic,* which is related to what has been referred to as *strong automaticity* (Kahneman & Treisman, 1984). Putting flankers around a familiar word (or other words around it, as in typical text) requires the operation of the filter to deliver just the features at the location of the target word to the SI domain. To accomplish this, the channel is aligned with the boundaries of the target word. Because the filter is implicated, we say that attention has been involved in the process. However, the filter need not be involved further than the narrowing to the word boundary, if the word is familiar. If the word shape is unfamiliar, we assume that the filter must be narrowed further and shifted from one familiar spelling pattern to another or from one (familiar) letter to another. Thus, relative to the part–word filtering required for identifying an unfamiliar word, the identification of a familiar word proceeds without any part–word filtering, once extra-word items have been filtered. In other words, a familiar shape may be said to be identified automatically (in the mandatory sense) if the identification process does not require the channel size to be narrowed further than the boundaries of the shape.

Neuroanatomical Correlates of the Domains of the Theory

There are suggestive parallels between most of the domains described in the present theory and anatomically separable structures in the monkey and human brain. Also, connections between the computationally based structures of the present theory appear to correspond to connections between parallel structures in the brain. Note that the schematic descriptions of connections between computational domains shown in Figure 3 indicate flow of information in both directions, and fibers that connect corresponding brain structures virtually always go in both directions.

Feature registration. The domain of feature registration has a parallel brain structure in V1, the striate area, and parts of the prestriate area (Hubel & Wiesel, 1977; Van Essen & Maunsell, 1983; Zeki, 1978), and possibly the lateral geniculate nucleus, given the large amount of forward and backward projective fibers between these structures. The present theory assumes that when a feature, such as an oriented line segment, is represented in these areas, its rate of information flow is affected by the orientations of other line segments in the neighborhood of this feature. In particular, it is assumed that rates of flow at the location of a target feature will be higher than rates of flow at the location of a flanking feature when the target and flanking features are different, but the rates will converge as the target and flanking features become more similar. Corresponding relations have been found in the firing patterns of cells of striate and prestriate areas of the macaque monkey by DeYoe, Knierim, Sagi, Julesz, and Van Essen, (1986), who presented oriented line segments in and around the receptive fields of single cells in areas V1 and V2. When the orientations of the lines in the center and surround were the same, the firing rate of the neuron was suppressed relative to its firing rate when the line segment was presented alone in the center. When the orientations of the lines in the surround were orthogonal to the orientation of the line in the center, there was little or no suppression of the firing rate of the neuron. Thus, the information flow rate at the location of an oriented line would appear to be affected substantially by the similarity of orientations of other lines in the immediate neighborhood.

Shape identification. The striate area projects through several intervening cortical areas to the inferotemporal lobe in the monkey (Cowey, 1985; Desimone, Schein, Moran, & Ungerleider, 1985; Ungerleider & Mishkin, 1982; Van Essen & Maunsell, 1983), where cells have been found to fire selectively to visual shapes such as colored rectangles (Moran & Desimone, 1985) and monkey paws and faces (Desimone, Albright, Gross, & Bruce, 1984; Gross, 1973). Cells in this area have extremely large receptive fields and will therefore respond to a shape in many locations, suggesting that location information is not coded here. In the human brain, recent evidence from positron emission tomography (PETscan) experiments (Peterson, Fox, Posner, & Raichle, 1988) has indicated that tasks involving the identification of words produce greater blood flow in the cortical area near the border between the occipital and temporal lobes. Thus, anatomical evidence suggests that the brain is organized to perform shape identification in an area that is separate from the area of feature registration and is probably located in the posterior ventral area of the cortex.

The filter. In the present theory, the filter domain is computationally located centrally among the other domains. Its corresponding structure in the brain is the thalamus, which also is centrally located anatomically to relay neural activity between many brain areas. Within the thalamus is the pulvinar, the largest nucleus in human thalamus, and the pulvinar is subdivided into four nuclei, the anterior, medial, lateral, and inferior pulvinar (Jones, 1985). In the monkey, the medial pulvinar nucleus projects to the inferior parietal lobule (e.g., Mesulam, Van Hoesen, Pandya, & Geschwind, 1977) and returning connections have also been found (Weber & Yin, 1984). In this animal, both the inferior and lateral pulvinar nuclei have been shown to connect reciprocally with striate and extrastriate cortex (Benevento & Davis, 1977; Ungerleider, Galkin, & Mishkin, 1980), and it appears that there are parts of the nuclei in the inferior and lateral pulvinar nuclei that project to more than one visuotopically mapped area of the extrastriate cortex, whereas other parts may project to one area only (Jones, 1985). Connections between striate cortex and lateral and inferior pulvinar nuclei preserve visuotopic mappings (Ungerleider, Galkin, & Mishkin, 1983), and the size of the receptive fields of these pulvinar cells have been found to increase with increasing eccentricity (Bender, 1981). The lateral pulvinar nucleus also connects reciprocally with the posterior parietal areas (Jones, 1985). Thus, it appears that posterior parietal areas and extrastriate (and inferotemporal) cortical areas, corresponding respectively to the gradient and shape identification domains of the present theory, project to common visuotopic maps or to maps that overlap in the pulvinar area of the thalamus.

Surrounding much of the pulvinar, and most of the thalamus in general, is a thin shell-like structure only a few cells thick, called the reticular nucleus. The cells in this structure project onto cells of the dorsal thalamus, and not to the cerebral cortex (Jones, 1975), and because gamma-aminobutyric acid (GABA) is transmitted by these cells (Houser, Vaughn, Barber, & Roberts, 1980; Ohara, Lieberman, Hunt, & Wu, 1983), they probably produce an inhibitory effect on cells of the dorsal thalamus, including the cells of the pulvinar (e.g., French, Sefton, & Mackay-Sim, 1984). All fibers projecting from the dorsal thalamus to cortex pass through the reticular nucleus, and where there exist spatiotopically organized fields of cells in the thalamus, the organization carries over to the reticular nucleus (Jones, 1985). For each set of fibers projecting from thalamus to cortex, other fibers return from the cortex to the thalamus in adjacently located pathways. As these fibers pass through the reticular nucleus, they send collateral axons into the nucleus

(Ohara & Lieberman, 1985; Schlag & Waszak, 1971), which in turn projects to areas in the immediate surround.

The reticular nucleus has been described as having the properties that could subserve the functions of selective attention (Crick, 1984; Skinner & Yingling, 1977; Yingling & Skinner, 1977). Crick proposed a theory at the neural network level in which thalamocortical cells at one location are enhanced in contrast to cells in the immediate neighborhood. In this manner, it would appear that a constrained area could be momentarily set up in the reticular nucleus that passes the activity of fibers from thalamus to cortex routed through the area and inhibits or even blocks the activity of nuclei whose fibers are routed through the surround and apparently also other nuclei in the thalamus some distance away. Therefore, the reticular nucleus with its lateral inhibitory network and connections with the thalamic relay nuclei, has the kind of structures that could instantiate the function of a filter mechanism, whereas the visuotopically organized subareas of the pulvinar, with their connections to appropriate cortical areas, could instantiate the function of the filter map.

Position analysis. Turning to the position analyzer domain in the theory, we recall that it is assumed to be driven, top-down, by higher order processes, and that it carries out the function in the theory of selecting a subregion of a representation of a visual object (in the present case, the center region). To our knowledge, this structure does not yet have a well-specified anatomical parallel. One could speculate that owing to its spatial function such a structure would be located in or near the posterior parietal cortex, with connections both to pulvinar nuclei and to frontal cortical areas concerned with the goal-directed nature of the computational routines it must execute.

Location expectation. The gradient that generates the shape of the V curve of reaction time is assumed to be represented in the location expectation domain of the present theory. The function of the location expectation domain may be instantiated by cells of the posterior parietal cortex, which are responsive to the visuotopic location of objects (Anderson, Essick, & Siegel, 1985; Mountcastle, Andersen, & Motter, 1981; Posner et al., 1984; Wurtz, Goldberg, & Robinson, 1980). Some of the evidence implicating this brain area arises from recordings from single cells when monkeys orient or are about to orient to objects in head-centered space (Anderson, Essick, et al., 1985; Mountcastle et al., 1981; Robinson, Goldberg, & Stanton, 1978). Other evidence is observed in human patients who suffer lesions in this area (Mesulam, 1981; Posner et al., 1984, in press). Assuming that a gradient represents momentary spatial expectations, then *each* hemisphere normally contains a gradient extending over *both* sides of the visual field (i.e., two redundant maps), and the two gradients are interconnected. Callosal projections of cells to corresponding fields of the posterior parietal cortex of both hemispheres have been confirmed in the monkey (Anderson, Asanuma, & Cowan, 1985; Schwartz & Goldman-Rakic, 1982). When one side of visual space is cued, the peaks of both gradients are formed at the location of the cue.

Because the proposed gradient in the location expectation domain controls the filter mechanism through a map in the filter domain, it would be expected that unilateral damage to the map in the filter domain itself would produce similar deficits in locating objects as damage to the location expectancy domain serving the same side. For corresponding neuroanatomical structures, lesions in pulvinar should produce similar losses in attentional localization similar to those produced by the lesions typically found in posterior parietal areas. Evidence relevant to this hypothesis is given in a recent study by Peterson, Robinson, and Morris (1987), in which GABA-related drugs were injected into a subnucleus of the pulvinar on one side of the brains of monkeys. The inhibitory GABA-agonist produced an attentional deficit in the contralateral visual field that is very similar to the deficit attributed to parietal lesions in humans reported in a study by Posner et al. (1984). In fact, both studies used the same precuing task to measure attentional performance. The present theory suggests that, in addition, pulvinar disfunctioning should also disrupt identification of parts of objects because the controlling connections from the position analyzer to the filter channel are mediated through the filter map.

Assuming that a gradient in the posterior parietal cortex represents the effects of spatial cuing, the gradient could activate striate and extrastriate areas by connections either through intervening cortical areas or through the pulvinar. If the differential activation pattern of the gradient were projected to striate and/or extrastriate areas, the effect of a gradient on shape identification could be produced without involving the filter mechanism. In such a case, an unflankered target, such as R or 7, should show a nonzero slope of reaction time in the present experimental task (cf. the lower curves of Figures 6 and 7). Evidence for such early cuing of spatial information seems to be indicated by event-related potential waveforms in spatial cuing tasks (Eason, 1984; Hillyard & Mangun, 1986; Hillyard & Munte, 1984).

The present theory assumes that two kinds of information are involved when the attention mechanism participates in shape identification, namely, location information and feature information. Separate pathways in the brain have been proposed for the processing of visual forms on the one hand and visual locations on the other (e.g., Gross, 1973; Held, 1968; Ingle, 1967; Trevarthen, 1968; Ungerleider & Mishkin, 1982). There is some evidence indicating that brain structures specializing in feature analysis differ from those that specialize in location analysis with respect to the kinds of neurotransmitters found in innervating axons. Morrison and Foote (1986) reported that in the squirrel monkey, the pulvinar and the posterior parietal cortical areas are more densely innervated by noradrenergic fibers than are geniculo-striate and inferotemporal structures.

We emphasize that the neurobiological evidence just described is not to be taken as the primary supporting evidence for the proposed theory. Rather, such evidence may suggest how the primate brain may instantiate proposed computational structures and operations.

General Summary

The theory of attentional operations in shape identification described here assumes that familiar shapes may be identified directly and automatically when they are presented in complete isolation, but when other shapes appear simultaneously near the familiar target shape, an attentional filter is required to block the processing of the distracting shapes. Specifically, the controls on the filter are as follows: (a) A gradient represented in the location expectation domain is assumed to bias processing at particular locations in the filter map such that filtering takes place more quickly in certain locations than in others. (b) In the feature registration domain, a profile of differential information flow across neighboring locations of features is copied to the filter map, and formation of a filter channel is facilitated at the locations of highest flow. For some cases in which the differential flow between feature locations is sufficiently high, a channel could be established without additional information flow to the filter map from other domains. (c) The position analyzer domain acts in a top-down fashion to increase processing at a specific subarea of the filter map (corresponding to a subarea of an object) in response to task goals and momentary variations in self-instructed routines. It is through this route that higher order processes are assumed to exert influences on selective attention.

The selection process of attention, as described in the present theory, has two major aspects, facilitation and inhibition. The facilitatory operation can be performed by several domains (singly or in combination): the PA domain (mediating higher order processes, top-down), the FR domain (from locations of salient features, bottom-up), and the LE domain (representing a spatial gradient), all of which can facilitate processing at a specific location or a range of locations. The inhibitory operations are assumed to exist within domains (e.g., the lateral inhibitory connections in the FR domain that are assumed to influence saliency of a feature), but the major attentional inhibitory influence is assumed to be performed by one domain, the filter domain, which is strategically positioned in the system to provide inhibitory adjustments on the combined facilitatory inputs, effectively blocking information flow at all locations except the one with the highest level of flow. The inhibitory computation on the combined inputs to the filter may be compared with the inhibitory inputs to a nerve cell that are typically positioned near the axon hillock and that react on the combined facilitatory inputs from a variety of other neurons that project upstream onto the cell body and dendrites. In the present theory, it would seem computationally advantageous that the inhibition operation be positioned where the facilitatory inputs converge, rather than earlier, so that inhibition can operate on the accumulated effect of all the facilitatory inputs, to further emphasize and sharpen the area of highest information flow. Thus, the present theory views selective attention as driven by a variety of domains that perform facilitatory operations, but by only one domain that performs inhibitory operations on the combined facilitations.

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