6

The Control of Visual Attention

Richard D. Wright and Lawrence M. Ward

> But [attention's] towering growth would appear to have been achieved at the price of calling down upon its builders the curse of Babel, "to confound their language that they may not understand one another's speech." For the word "attention" quickly came to be associated ... with a diversity of meanings that have the appearance of being more chaotic even than those of the term "intelligence." (Spearman, 1937, p. 133)

Attention is a foundational concept in cognitive psychology. Many researchers have credited it with a central role in the "cognitive revolution" of the 1950s and 1960s (e.g., Broadbent, 1958; Egeth, 1992; Neisser, 1967). It is, however, a concept with a stormy history, as the above quotation indicates, and there was little agreement until recently about how it should be defined. Spearman (1937) chronicled many proposed definitions including clearness, vivacity or intensity of percepts or concepts, an attitude of mind, a definite process or special stage in a process, the relative proportion of activated traces to all memory traces, some form of energy or desire involving will or effort, and the sensation of exertion of will. Since 1937, definitions or metaphors such as a filter (Broadbent, 1958), a skill (Neisser, 1976), a selective attenuator (Treisman, 1964), a resource (Kahneman, 1973), a "spotlight beam" within which processing is enhanced (Posner, 1980), a "zoom lens" (Eriksen & Yeh, 1985), a "glue" that binds features together (Treisman & Gelade, 1980), and a decoupler of modules from public communication channels (Navon, 1989), among others, have added to the confusion. Moreover, a number of different aspects of attention (e.g., capacity, selectivity, control, relation to consciousness, relation to arousal) have been engaged by specific paradigms and emphasized by particular writers (e.g., Solso, 1991). Recently, however, some definite progress has been made in understanding how attention to locations and/or objects in visual space is controlled. This research has been carried out within several closely related experimental paradigms including those that allow conclusions to be made about physiological mechanisms. It has emphasized the way in which shifts of attention in visual space can be evoked by stimuli and by goals, and how these shifts are related to the control of eye movements. Although there are no final answers yet, the body of data amassed so far has several clear implications for our understanding of attention control processes. It also suggests integrative models and further research. We summarize some of these implications and propose one possible integrative model that has interesting implications for how we understand attention more generally.

Shifts of visual attention are changes in the spatial location to which we attend. They usually accompany eye movements but can also occur independently of eye fixation. For example, suppose you are sitting in a restaurant having dinner with a friend. While your eyes are fixed on your companion's face and you are listening intently to what is being said, your attention may stray to the interesting person at the next table. Your eyes have not moved but for a moment you are not attending to the object of your gaze. Two of the primary goals of contemporary research on this phenomenon are to determine when attention shifts are under voluntary control and when they are more reflexive, and to examine the nature of the relationship between attention shifts and eye movements.

More than a century ago, Helmholtz conducted an experiment to test his ability to shift visual attention independently of eye fixation (see Warren & Warren, 1968). He fixed his eyes on an illuminated pinhole in the centre of a dark field of large printed letters and, on each trial, illuminated the display with an electric spark. The illumination did not last long enough for an eye movement to be made away from the fixation point while the display was visible, and Helmholtz was unable to perceive all of the letters or even all of those near the fixation point. By deciding in advance of the illumination which part of the display to attend to, however, he was able to recognize single groups of letters in the attended region. Moreover, he was able to voluntarily shift his attention to different regions of the display while maintaining eye fixation on the central, illuminated pinhole. This experiment is often cited as the first scientific demonstration of the independence of visual attention shifts and eye fixation.

James (1890) stated that when we selectively attend to an object, the mind "takes possession" of it even though other objects are present that the mind also could have taken possession of (cf., LaBerge, 1990a). He described "paying attention" in terms of resources that have their greatest concentration at the focal point and a decreasing concentration as a function of increasing distance from the focal point. James also proposed that there are two domains of attention – the *immediate sensory domain* and the *voluntary intellectual domain*. The first involved, in

his terms, the accommodation or adjustment of sensory organs. The second domain involved anticipatory preparation from within the cognitive centres concerned with the object attended to. This proposal foreshadows one of the central aspects of more recent investigations – the distinction between voluntary and involuntary attentional processes. Titchener (1910), among others, studied involuntary processes after observing that abrupt flashes in the visual periphery appear to draw attention to their locations. Thus, contemporary research on the control of attentional processes was anticipated in proposals made 100 years or more ago.

Despite the pioneering efforts of Helmholtz and James, studies conducted long after their proposals produced very little supporting evidence (e.g., Grindley & Townsend, 1968; Mertens, 1956; Mowrer, 1941). In fact, it was not until the 1970s and the advent of location cueing experiments that significant empirical evidence began to accumulate to substantiate the claim that visual attention *can* be aligned independently of eye fixation.

Location Cueing and Shifts of Visual Attention

Visual attention is often described in terms of a focal point that is aligned with different locations in space as we inspect our visual world. These attentional alignments can also be initiated in response to cues about the probable locations of impending targets that interest us. Many location cueing experiments have been conducted to study the "beneficial" effect of a valid cue and the "negative" effect of an invalid cue on target detection and identification responses (e.g., Posner, Nissen, & Ogden, 1978; Posner & Snyder, 1975; Posner, Snyder, & Davidson, 1980). Typically (e.g., 70% of trials), the location information conveyed by a cue is a valid indicator of where the target will appear on that trial (see Figure 1). And, in the remaining cases (e.g., 30% of trials), cue information is either invalid or neutral. Like valid and invalid cues, neutral cues provide a temporal warning signal about the impending target's onset. But they are referred to as "neutral" because they are supposed to provide no information about target location. Their purpose is to serve as a baseline measure for a cost-benefit analysis of location cueing effects. That is, the mean response times or accuracies for trials involving valid and invalid cues are compared to the same measures for trials involving neutral cues. The "valid vs. neutral comparison" provides a measure of the *benefit* of valid cueing, and the "invalid vs. neutral comparison" provides a measure of the *cost* of invalid cueing (see Figure 1).

While cost-benefit analysis has played an important role in the study of attentional processes, there has also been a growing awareness of its limitations in recent years (see e.g., Jonides & Mack, 1984; Wright,
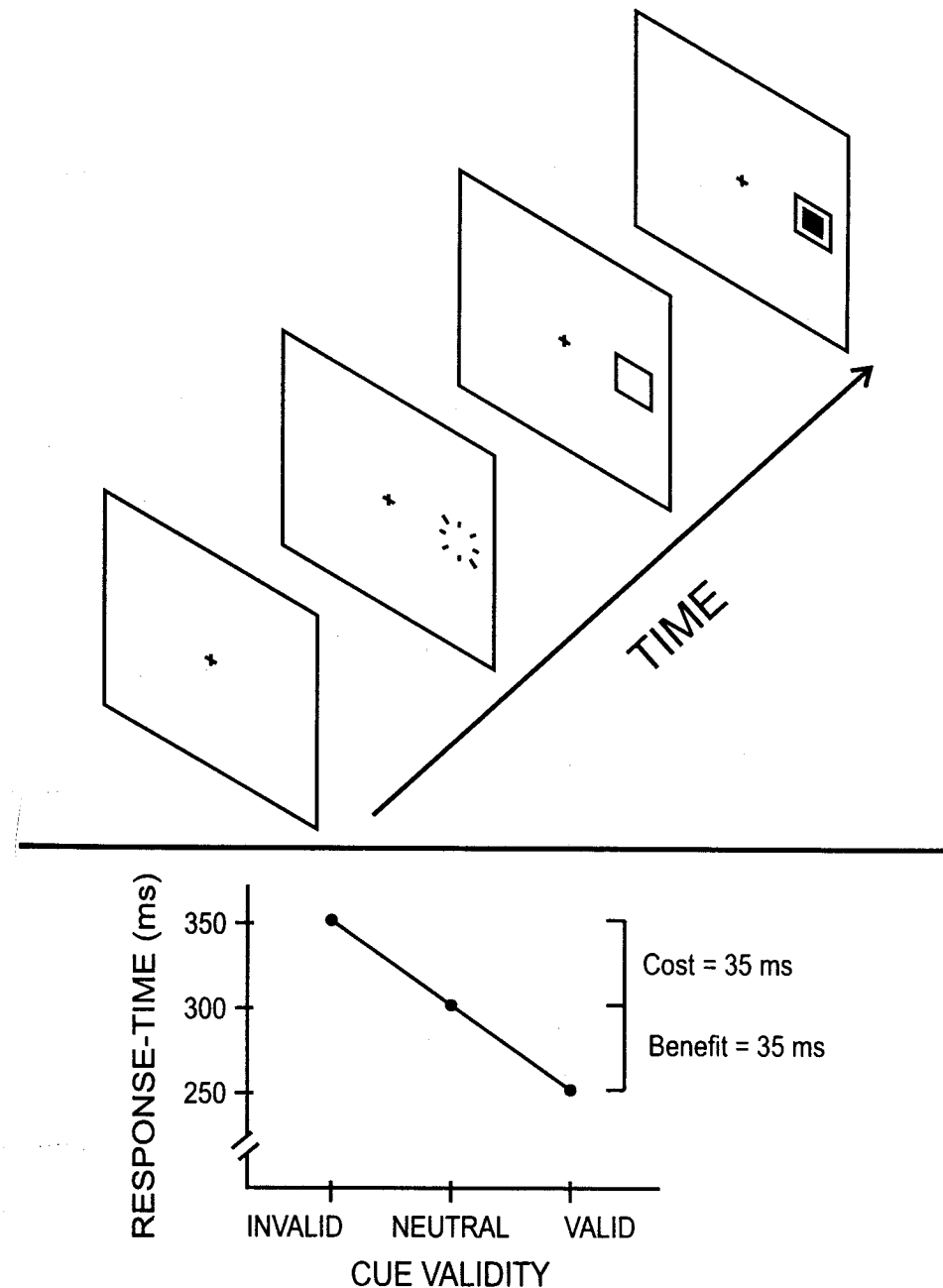

Figure 1: Pattern of data obtained by Posner et al. (1978) indicating the response-time cost and benefit of invalid and valid location cueing.

Richard, & McDonald, 1995). The main concern is about the neutral cue baseline measure, and particularly when examining the effects of direct location cues (those that appear at or near the locations of targets). More specifically, neutral cues are difficult to present in a truly location-non-specific manner. Several strategies have been adopted to compensate for this including foregoing neutral cueing and using only a "valid vs. invalid comparison" to get what amounts to a "cue effectiveness" measure (Wright & Richard, 1996). Without the neutral baseline, however, it is unclear whether or not this comparison reflects costs or benefits. That is, without a neutral baseline, there is no way of knowing the relative effectiveness of valid vs. invalid cues. Another strategy is to minimize the degree to which the neutral cue has a specific position by, for example, presenting a uniform flash of the entire display background (Mackeben & Nakayama, 1993). Selecting an appropriate neutral cue is more straightforward when examining the effects of symbolic location cues. All types of symbolic cues are usually presented in the central location, and therefore do not convey potential target locations on the basis of their physical position. For a detailed discussion of this issue, see Wright et al. (1995). In this chapter and many other articles in the literature, references to response facilitation and inhibition due to location cueing are usually based on some form of cost-benefit analysis.

There are two main types of location cues. *Symbolic cues* (e.g., arrows or digits) can be used to initiate an attention shift by virtue of symbolic information about the probable location of the target. They are also called central cues, in part, because they are usually presented at the centre of the display (Posner, 1978). *Direct cues* (e.g., outline boxes, bars, or dots) initiate attention shifts merely by appearing at or near the probable location of the target, as in Figure 1. They are also called peripheral cues, in part, because they (and targets) are usually presented at noncentral locations within the display (Posner, 1978). While the terms *central* and *peripheral* refer to the location of the cue in the visual field or on the retina, location does not fully indicate the fundamental difference between the two types of cues. That is, central cues do not have to be presented in the centre of the stimulus display to be effective, and peripheral cues remain effective even when presented centrally (e.g., Eriksen & Colgate, 1971). For this reason, other pairs of terms such as "push vs. pull cue" and "information vs. stimulus cue" are also found in the attention shift literature. The primary difference between them is that the direct type of cue summons attention to the location of its onset without the need for interpretation of cue meaning. On the other hand, the symbolic type of cue does require some initial interpretation of cue meaning before attention can be shifted to the cued location (e.g., Remington, 1980).

Shifts of attention initiated by symbolic vs. direct cues have been referred to as "intrinsic vs. extrinsic" (Milner, 1974), "endogenous vs. exogenous" (Posner, 1978), and "voluntary vs. involuntary" (Jonides, 1981; Luria, 1973; Müller & Rabbitt, 1989). The latter pair of terms is common because shifts initiated by a symbolic cue can be voluntarily suppressed while shifts initiated by a direct cue can be difficult to suppress (e.g., Jonides, 1981, 1983; Müller & Rabbitt, 1989). When an observer chooses to use a symbolic cue to aim an attention shift, the target's probable location is incorporated into a *computational goal* for carrying out the task (i.e., use the cue information to shift attention to the expected target location). Therefore, in this chapter, we use the more general term, *goal-driven* control, when referring to the initiation of endogenous, voluntary, and intrinsic attention shifts.

While shifts of attention triggered by direct cues can be difficult to suppress, there are some situations in which a direct cue onset will *not* result in a reflexive shift of attention to its location. Yantis and his colleagues found that while abrupt-onset visual stimuli can trigger attention shifts to their locations, observers can also override such shifts if they are actively focusing their attention elsewhere when the abrupt-onset stimuli appear (e.g., Yantis & Jonides, 1990). In other words, an attention shift is not a mandatory consequence of a direct cue onset. Without this capacity to suppress attention shifts to stimuli that suddenly appear in our visual field, we would be distracted by many irrelevant visual events. And our performance of any task requiring sustained attention and vigilance would be disrupted. Therefore, the effect of direct cue onsets is not entirely involuntary. In this chapter, we use the more general term, *stimulus-driven* control, when referring to the initiation of exogenous, involuntary, and extrinsic attention shifts.

Several studies have been conducted to test the claim that direct cues "capture" attention more readily than symbolic cues do. One of these studies involved a comparison of direct cue and symbolic cue effectiveness when subjects performed a target-identification task and a concurrent memory-load task (Jonides, 1981). Symbolic cue effectiveness was diminished by increases in memory load but direct cue effectiveness was not. It was concluded that attention shifts were initiated more automatically by the direct cues than by the symbolic cues because the latter required attentional resources that were also needed to perform the competing memory load task. Direct cue effectiveness, on the other hand, appeared to be independent of the need for attentional resources (cf. Schneider, Dumais, & Shiffrin, 1984). Also, explicit instructions to *ignore* the location cues decreased the effectiveness of symbolic cues more than that of direct cues (Jonides, 1981). Furthermore, decreasing cue validity (e.g., valid cue on 20% as opposed to 80% of trials as in the

previous experiments) also decreased the effectiveness of symbolic cues more than that of direct cues (Jonides, 1981; Kröse & Julesz, 1989; Müller & Humphreys, 1991). Presumably, this is because subjects do not voluntarily use low validity cues. These results therefore imply that direct cue effects are more reflexive than symbolic cue effects.

Claims about the "automaticity" of direct cue effectiveness should be qualified. This effectiveness appears to depend on the nature of the cue's onset and on the current state of the observer's attentional focus. Location cues can have either an *abrupt-onset* or a *gradual-onset* (see e.g., Todd & Van Gelder, 1979; Yantis & Jonides, 1984, 1990). Abrupt-onset stimuli appear suddenly in the visual field and can be targets (e.g., letters, flashes of light) or cues (e.g., bar markers, arrows, brightened boxes). Gradual-onset stimuli (cues or targets) emerge less suddenly, either because they are revealed by the removal of camouflage elements or because they are "turned on" so slowly that luminance changes over time are below "onset thresholds" (see Figure 2).[1] The results of several experiments indicate that targets with abrupt onsets capture attention more effectively than those with gradual onsets (e.g., Yantis & Jonides, 1984). In some cases, however, when search is initiated by a symbolic cue, the time to respond to abrupt-onset targets does not differ from that to respond to gradual-onset targets (Yantis & Jonides, 1990). This finding suggests that the attention-capturing effectiveness of an abrupt-onset stimulus appears to be attenuated if an observer is, at the same time, actively focusing on a symbolic cue at another location (see also, Folk, Remington, & Johnston, 1992). Thus, an abrupt-onset stimulus can initiate an attention shift to its location in a stimulus-driven manner, but the shift may not occur if attention is actively focused or engaged elsewhere.

Differences in direct cue and symbolic cue effectiveness as a function of cue-target-onset-asynchrony (CTOA) are another indication that the former elicit stimulus-driven shifts and the latter elicit goal-driven shifts. In particular, valid direct cues appear to be maximally effective when the CTOA is approximately 100 ms, but this effectiveness begins to attenuate with further CTOA increases (e.g., Müller & Findlay, 1988; Shepard & Müller, 1989).[2] On the other hand, the effectiveness of symbolic cues appears to increase gradually as the CTOA is increased from 0 to 300 ms, and effectiveness appears to be sustained at a maximum level with further CTOA increases (e.g., Müller & Findlay, 1988; Shepard & Müller, 1989). In some cases, the effectiveness of direct cues can be sustained at slightly lower than the maximum level with CTOAs larger than 100 ms (Cheal & Lyon, 1991). Presumably, the occurrence of a sustained direct cue effect at CTOAs larger than 100 ms depends on whether this cue also functions as a symbolic cue after the initial reflexive effects of cue onset subside.[3]
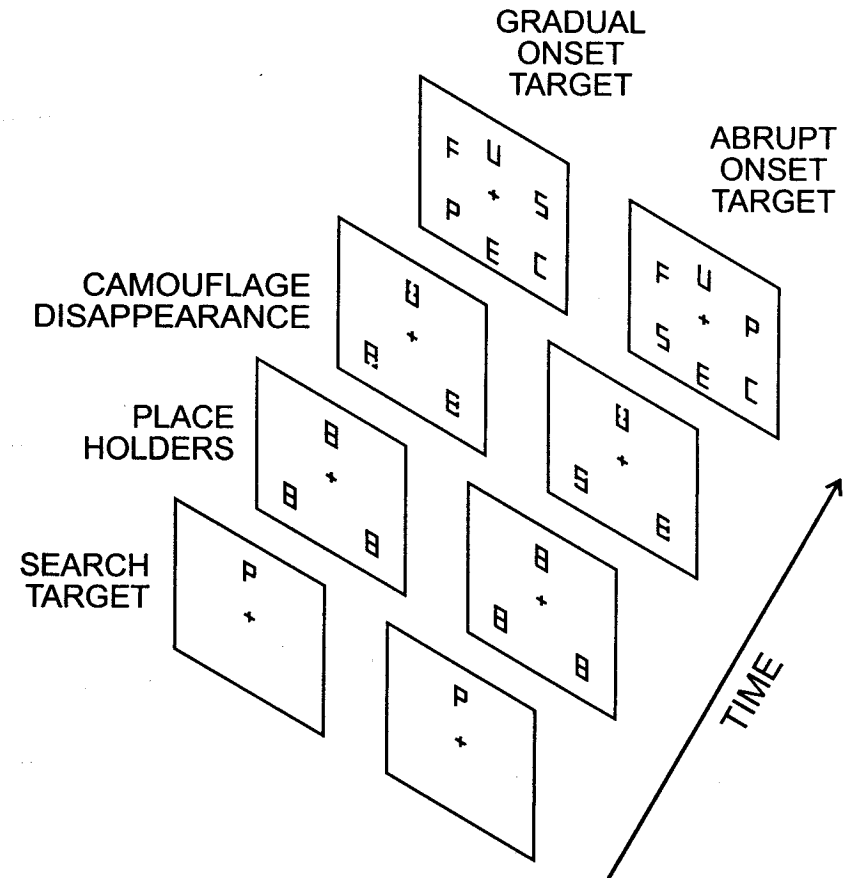
Figure 2: Abrupt-onset and gradual-onset presentations of the target P. The stimulus sequence on the left involves the gradual removal of irrelevant camouflage lines from a stimulus that is already present. The stimulus sequence on the right involves the abrupt appearance of a stimulus in a previously blank location.

The transient nature of direct cue effectiveness is also evident when studying the interference caused by irrelevant abrupt-onset stimuli. In particular, if an irrelevant abrupt-onset stimulus is presented *less* than 100 ms after cue onset, a stimulus-driven shift will still be triggered by the relevant direct cue. If an irrelevant abrupt-onset stimulus is presented *more* than 100 ms after the relevant direct cue, however, the former can disrupt the shift of attention and cause it to be made instead to the irrelevant stimulus location (Müller & Rabbitt, 1989). Thus, direct cueing appears to be resistant to interference for only about 100 ms.

In general, stimulus-driven attention shifts appear to be triggered rapidly by abrupt-onset direct cues, and the transient nature of direct-
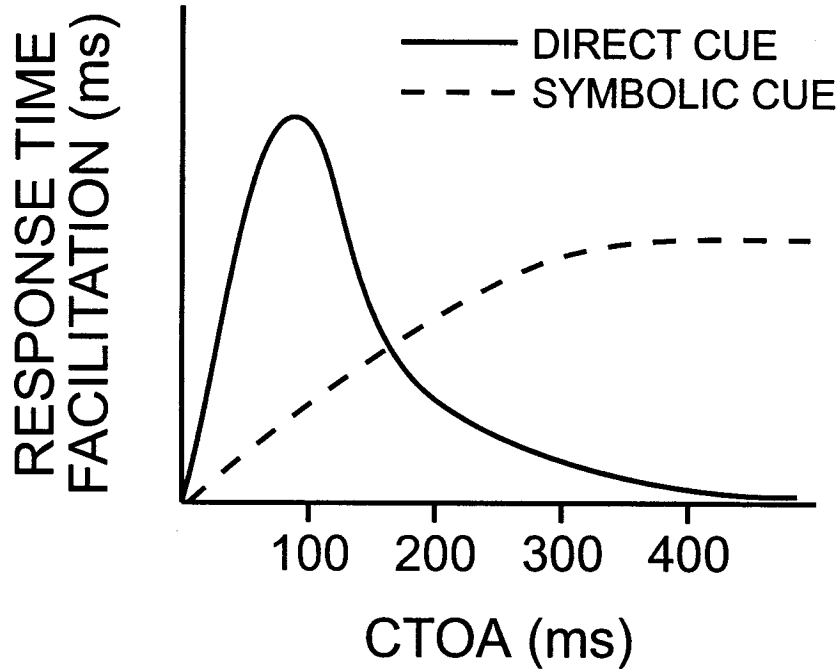
Figure 3: Typical data indicating the time-course of response-time facilitation produced by direct and symbolic locations cues as a function of cue-target-onset-asynchrony (CTOA). The dashed line represents direct cueing effectiveness and the solid line represents symbolic cueing effectiveness.

cue effectiveness is indicated by a decline in response-time facilitation when CTOAs are increased beyond 100 ms. Goal-driven shifts, on the other hand, appear to be initiated less rapidly, and the time required to focus attention on a symbolic cue and interpret it (and perhaps to disengage attention after the interpretation) may account for reports that symbolic cues require CTOAs of 300 ms or more to be maximally effective. The difference in the time course of effectiveness of the two types of cues is summarized in Figure 3.

Questions have also been raised about whether the costs and benefits of location cueing reflect changes in perceptual processing or whether they arise from changes in an observer's criterion for reporting the presence or identity of stimuli (Lappin & Uttal, 1976; Shaw, 1983). Researchers have attempted to determine whether faster response times for targets presented on valid cue trials (benefits) arise from greater perceptual sensitivity at the target location or from a more liberal decision criterion, and whether slower response times for targets presented on invalid cue trials (costs) arise from lesser sensitivity at the target location or from a more conservative criterion. Signal detection theory

provides a way to measure perceptual sensitivity (d') independently of the decision criterion (β) and is usually used to differentiate between these two possibilities (e.g., Green & Swets, 1966/1974). Although the results of early experiments using this approach were equivocal, more recent data indicate that location cueing does affect perceptual processing (e.g., Bonnel, Possamai, & Schmidt, 1987; Downing, 1988; Müller, 1994; Müller & Humphreys, 1991; Possamai & Bonnel, 1991). That is, perceptual sensitivity to targets appearing at cued locations is greater than that to targets at uncued locations. Moreover, the greatest change in perceptual sensitivity at cued locations appears to follow the onset of direct cues as opposed to symbolic cues (Müller, 1994).

Visual Attention Shift Models

Several models have been proposed to account for attention shifts. One of these is the analog spotlight model. According to some theorists, analog mechanisms shift from one state to another by traversing the set of intermediate states (e.g., Shepard, 1975). Advocates of analog attention shifts claim that as the focal point is "moved" from one location to another, it also traverses the intermediate spatial locations like a metaphorical spotlight (see Figure 4). The validity of analog spotlight models has been tested by studying how costs or benefits of location cueing vary with the distance between the cue and the target. These studies are based on the assumption that as this distance is increased, more time will be required to "redirect" an analog spotlight of attention from an invalid cue location to the target location. Some studies indicate that increases in invalid-cue/target distance lead to *linear* increases in response time, which is consistent with the notion of a constant velocity spotlight (e.g., Shulman, Remington, & McLean, 1979; Tsal, 1983). Other researchers, however, have found nonlinear increases in response time with increasing invalid-cue/target distance, which implies that analog spotlight velocity is either variable or perhaps constant but defined relative to distance in visual angle units scaled by visual receptive field size (e.g., Downing & Pinker, 1985). Still others have found that costs or benefits did not vary with invalid-cue/target distance, which implies that if the attention shift involves an analog spotlight, its velocity is proportional to the distance it moves (e.g., Remington & Pierce, 1984). Critiques of this research have implicated other possible reasons for the constant-velocity results (e.g., Eriksen & Murphy, 1987; Yantis, 1988). Although analog attention shift models are appealingly simple, a lack of unequivocal empirical support has limited their usefulness.

An alternative explanation of the proportional-velocity results is that shifts of an attentional focal point are discrete. That is, during an
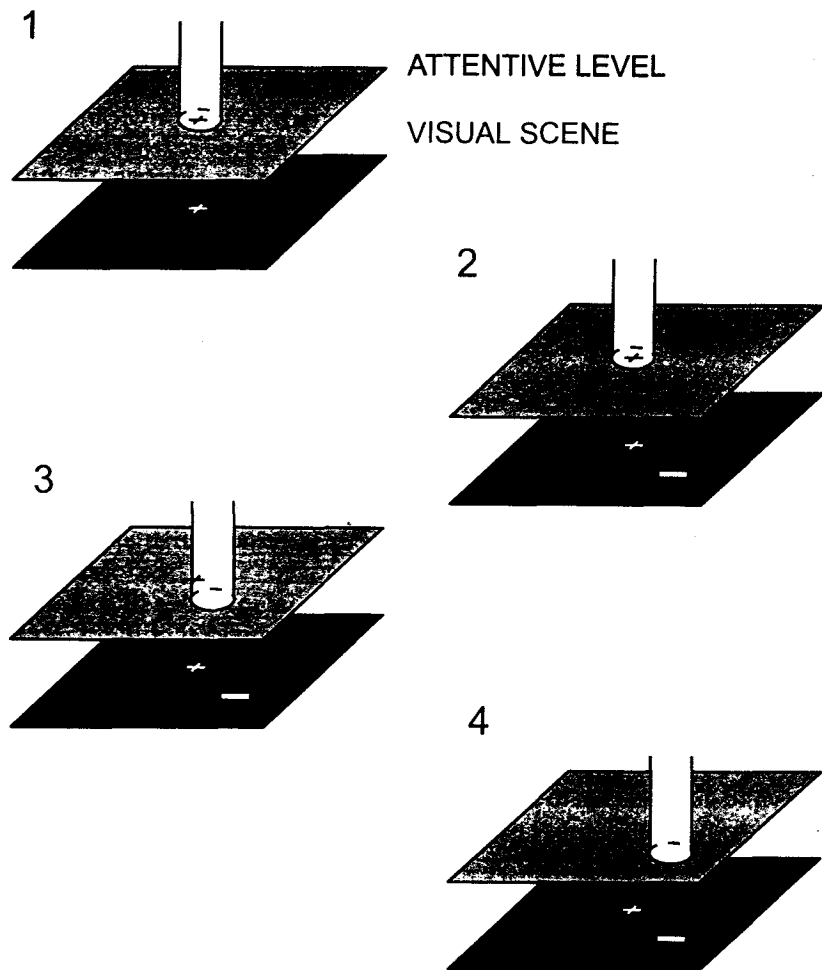
Figure 4: Analog spotlight account of a visual attention shift from the centre of a display to the location of the horizontal line stimulus. The black surface is the stimulus display, and the grey surface is a mental representation of it. The spotlight is said to be analog because it remains "turned on" when shifted.

attention shift, the beam is "turned off" and does not traverse the intermediate locations between the initial point and the destination (see Figure 5). A pure discrete spotlight model requires that costs and benefits be unaffected by changes in invalid-cue/target distance. In other words, the time required to turn off the spotlight at the initial point and turn it back on again at the destination should not be a function of the distance between the two locations. Evidence supporting such a model has been obtained, for example, in a series of studies in-
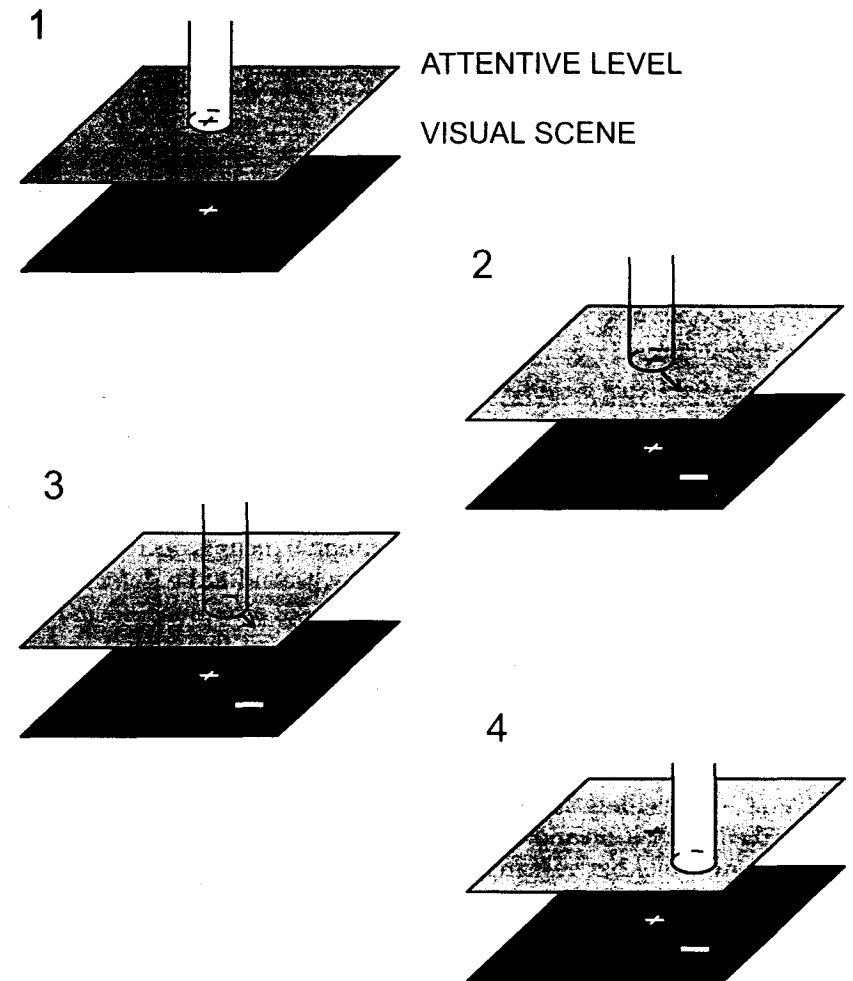

Figure 5: Discrete spotlight account of a visual attention shift from the centre of a display to the location of the horizontal line stimulus. The spotlight is said to be discrete because it is "turned off" during a shift and then "turned on" again at the destination.

volving multiple simultaneous direct cues (Eriksen & Webb, 1989; Eriksen, Webb, & Fournier, 1990). The main finding was that differences in the distances between these cues did not affect the time required to identify targets at the cued locations. While subjects appeared to check the cued locations serially, the time required to do so was independent of the distance between the locations. Other results have also suggested that, in some cases, attention shift time is independent of shift distance (Kwak, Dagenbach, & Egeth, 1991; Sagi & Julesz, 1985; Skelton & Eriksen, 1976). Thus, there is considerable

empirical support for the notion of discrete attention shifts and they have been assumed to occur by many researchers who have attempted to associate attentional processes with specific brain areas (e.g., Posner, Petersen, Fox, & Raichle, 1988).

One of the limitations of analog and discrete spotlight models is the lack of a mechanism that systematically varies the spatial extent of the beam. This is a concern because there is evidence that attentional focus that can range from a broad extent throughout the visual field to a fine focus at a particular location of interest (e.g., Eriksen & Hoffman, 1974; Eriksen & Yeh, 1985; Jonides, 1980; LaBerge, 1983; Ward, 1985). Eriksen and his colleagues (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985) proposed that the attentional focal point is characterized by a distribution of attention resources. They also proposed that the distribution of resources and the spatial extent of focused attention have a reciprocal relationship like that between the resolving power and spatial extent of a camera's zoom lens. That is, attentional resources become more concentrated as the spatial extent of attentional focus is decreased. Furthermore, when attention is shifted, it is was said to be defocused at one location (an increase in the spatial extent of attentional focus) and then refocused at another location (a decrease in the spatial extent). Most descriptions of focusing models imply that they are analog in the sense that the attentional focus remains "turned on" when its spatial extent changes. Figure 6 shows how attention would be shifted between locations in the visual field if such a mechanism was required to traverse intermediate states of focus (i.e., narrow to broader to broadest at the old location and then broadest to less broad to narrow at the new location). Other researchers have suggested that an attentional zoom lens may have only two states – a broad, diffuse focus encompassing the entire visual field and a narrow focus (perhaps 1° to 2° of visual angle) on a specific location – and therefore that focusing involves a discrete switch between these states (called the "Law of Two Levels" in the early twentieth century and adopted by some contemporary researchers, e.g., Jonides, 1980). Still others have argued that adjustments of the zoom lens are discrete while not making specific claims about the number of different states of focal resolution (e.g., Shepard & Müller, 1989, p. 152). In general, the distinction between analog and discrete mechanisms can be understood as attention remaining "turned on" or engaged during shifts from one spatial locus to another in the analog case versus attention being "turned off" or disengaged during shifts in the discrete case.

To summarize the points made in this section, stimulus-driven attention shifts appear to be initiated rapidly in response to the *transient* effect of abrupt-onset direct cues, but only if attention is not actively
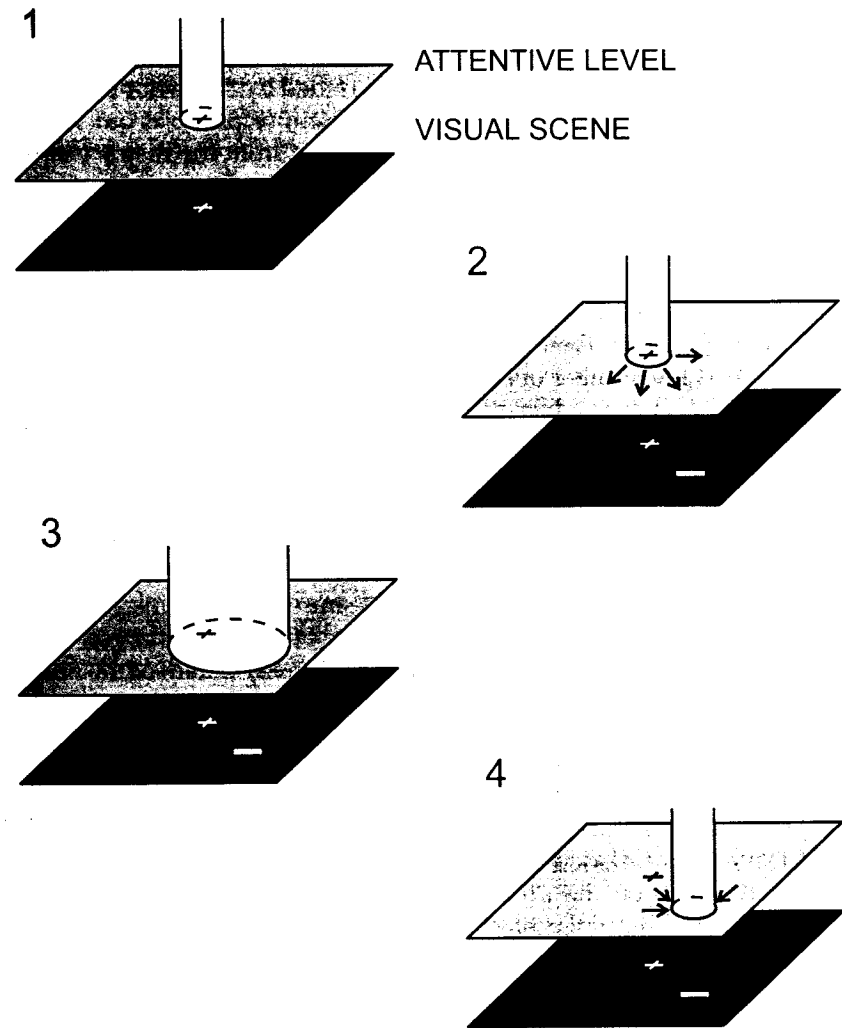

Figure 6: Analog zoom lens account of a visual attention shift from the centre of a display to the location of the horizontal line stimulus. The zoom lens is shifted by increasing in spatial extent and decreasing again around the destination.

engaged elsewhere. Goal-driven attention shifts made in response to symbolic cues appear to be initiated voluntarily and less rapidly, and only after interpretation of cue meaning. Most evidence indicates that stimulus-driven shifts are discrete as opposed to analog.

Preattentive and Attentive Visual Processing

Neisser (1964) was among the first of the researchers in the modern era to make a distinction between preattentive and attentive visual

processes. Much of this work was based on the study of visual search in controlled laboratory experiments. Observers in these experiments typically searched for a target letter surrounded by distractor letters in order to make a Target Present or Target Absent response as quickly as possible. If the target was sufficiently different from the distractors in such a way that it stood out, responses were rapid. For example, if the target letter was roundish (e.g., O or Q) and the distractors were angular (e.g., M, N, Z, X, W), then the target's location was often immediately apparent. Rapid detection of the target's presence soon came to be known as "pop out." If the target was similar to the distractors (e.g., both were angular), then search was slower, effortful, and required more time as the number of items in the search set was increased. This "set-size effect" occurred, in other words, if the target did not stand out from the distractors by virtue of a unique feature, but virtually no set-size effect occurred if the target had a unique feature not possessed by the distractor items. This was taken as evidence for two separate stages of visual processing. More specifically, Neisser (1964) suggested that a positive relationship between the number of search set items and Target Present or Target Absent response time implies that items are being serially inspected to determine whether or not they are the target. Conversely, when the response time was virtually independent of the number of search set items, as is the case when the target stands out by virtue of possessing a unique feature, a preattentive stage of processing was thought to be mediating target detection. The preattentive/attentive distinction has shaped much of the thinking about visual search processes since Neisser's (1964) proposal.

Treisman and Gelade (1980) developed an explanation of these results that builds on the preattentive/attentive proposal outlined by Neisser (1964). They suggested that, at the preattentive analysis stage, feature information (e.g., colour, orientation, motion) is analyzed in parallel throughout the visual scene by separate feature analysis modules. The presence of a unique-feature target (e.g., one with a unique colour) was said to be immediately apparent because the target is the only one of its type detected by the relevant feature module. On the other hand, the presence of a conjunction target (e.g., one with a unique shape/colour combination) was said to require attention because comparisons had to be made across feature modules to determine the feature combination of objects at particular locations. Conjunction-target search could involve, for example, checking the information in the colour module and then the shape module to find out the colour/shape combination of, say, the third object from the left in a stimulus display. Thus, in Treisman and Gelade's (1980) terms, attention would be required to "glue" these features together (integrate them) to form a perceptual object. They called this proposal the *feature-integration theory*. When a scene is inspected in a serial manner to locate a conjunction target, attention was therefore said to glue features together to determine whether or not each object's combination matched that of the target.

Feature-integration theory can be described with a map-based model. In Figure 7, each of a number of *feature maps* are connected indirectly through common inputs to a *master map of locations*. And each feature map corresponds to a different dimension (e.g. colour, orientation, motion). When a unique-feature target pops out, it is registered within the feature map in question (e.g., the target is the only red object in the display) and the observer immediately detects its presence. When this type of target is located, the feature map sends a signal that causes focused attention to be aligned with the corresponding location of the red object in the master map of locations. When a conjunction target is located, as in Figure 8, focused attention is aligned in a serial manner with each of a number of locations in the master map. And, at each master map location, information about features at the corresponding location within each feature map is accessed. In this way, according to Treisman and Gelade (1980), feature integration occurs. One property of the feature-integration process is that focused attention can only be positioned at one location at a time within the location map and, therefore, only one set of object features can be integrated at a time. The spotlight metaphor is sometimes used to describe movements of focused attention from one location to another within the master map of locations.

The effects of location cueing on visual search efficiency have been studied to test the claim that conjunction-target search involves serial attentive processing while unique-feature-target search occurs on the basis of preattentive analysis. It was expected that the presentation of a location cue at the impending target's location immediately prior to the onset of the search display (within 100 ms) would have a greater effect on conjunction-target search times than on feature-target search times. The results of several experiments confirmed this prediction (e.g., Nakayama & Mackeben, 1989; Treisman & Gelade, 1980). The presentation of a location cue did little to increase the speed of the already rapid feature-target search. This is further evidence that the detection of a unique-feature target is mediated primarily by preattentive processes because facilitating the alignment of focused attention had no effect on the operations involved. On the other hand, the facilitative effects of location cueing on conjunction-target search times indicates that serial alignments of the attentional focal point are involved.
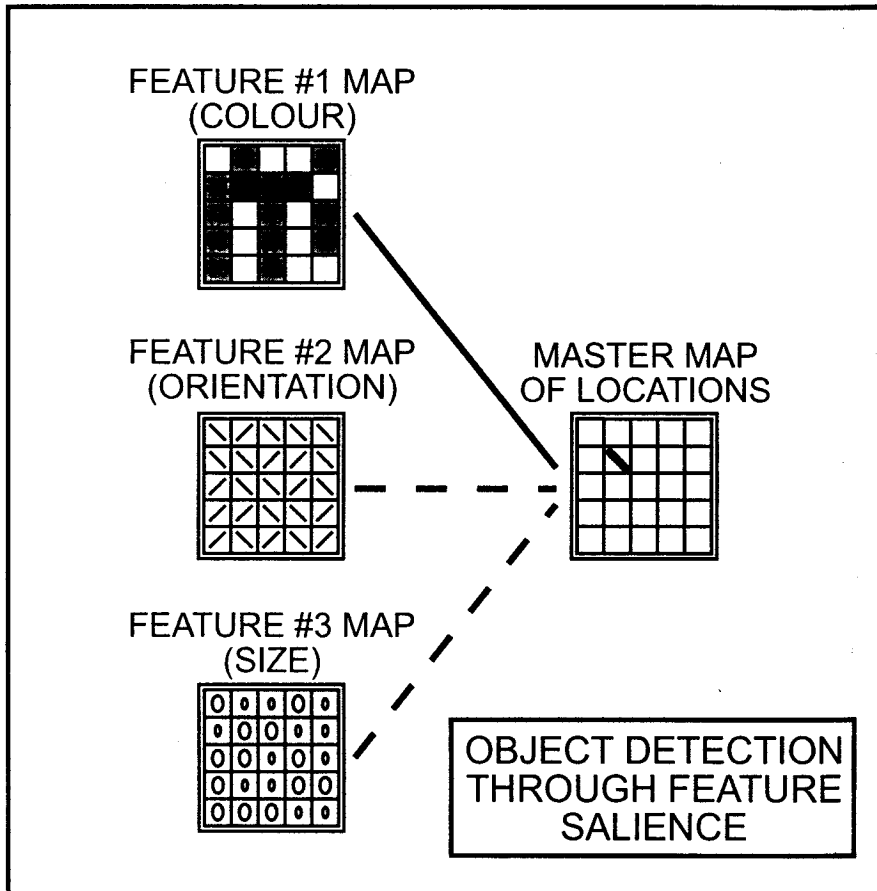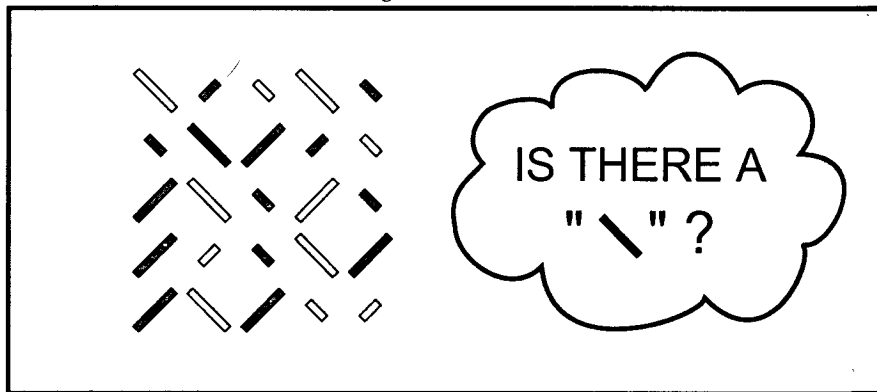
Figure 7: A simplified map-based account of feature integration theory. In this case, the larger white "upper-left/lower-right" bar pops out of the display because its unique colour triggers activation in the colour map. See Treisman and Gormican (1988) for a detailed description of the theory.
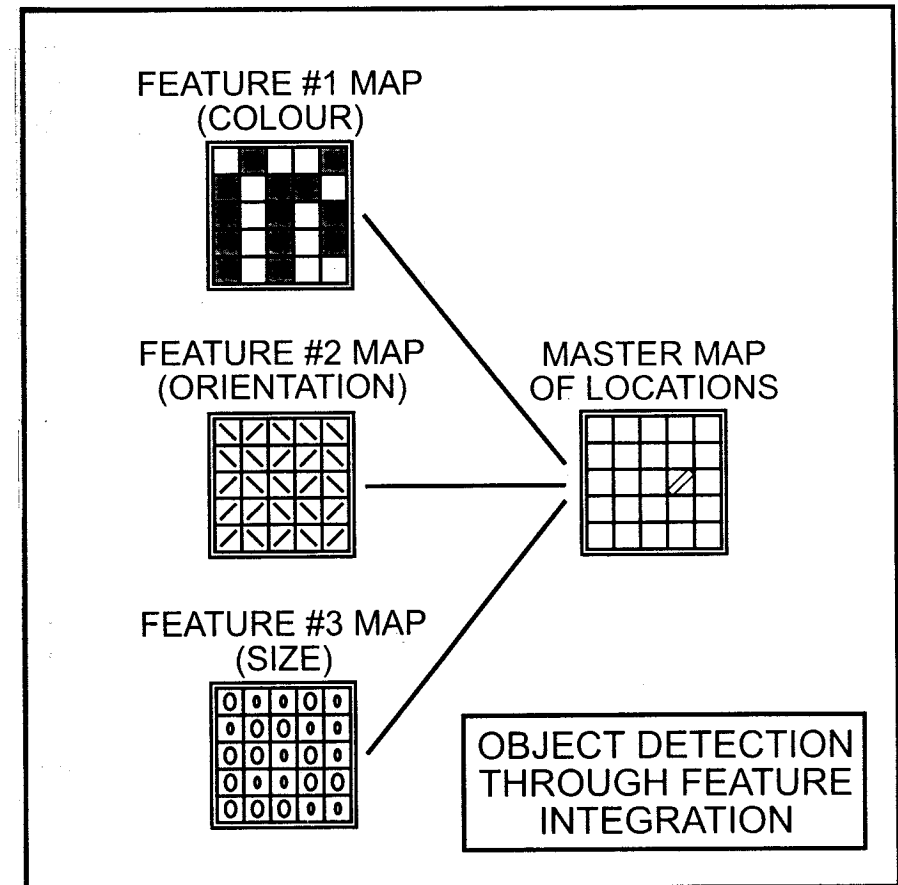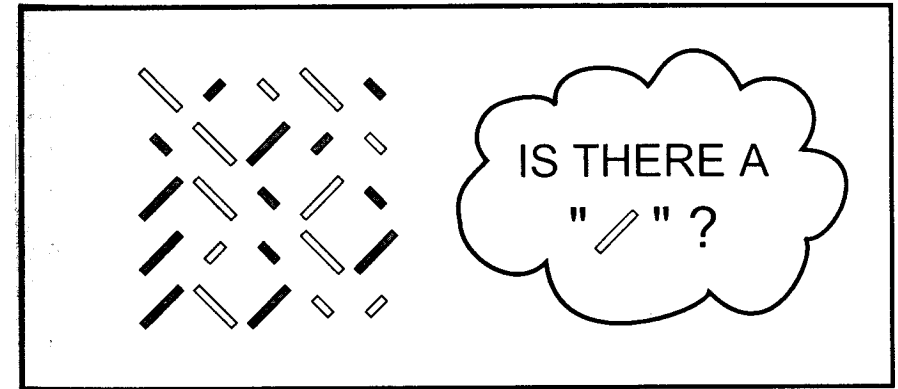
Figure 8: Another simplified account of feature integration theory. In this case, the larger black "upper-right/lower-left" bar does not pop out and must be serially searched for because it has no unique feature within any of the feature maps.

Preattentive Location Encoding

Several researchers have attempted to determine whether attention is confined to a single focal point or can be simultaneously divided between a number of different locations. Although some disagree, there is a general consensus in the literature that the attentional focal point is unitary and nondivisible (e.g., Posner, 1980). This claim is supported by the results of experiments in which two symbolic cues are presented simultaneously and observers must try to direct their attention to both cued locations at the same time in anticipation of the impending target (e.g., Kiefer & Siple, 1987; McCormick & Klein, 1990). The data are a compelling indication that we are unable to do so and still perform visual tasks with the same efficiency as when attending to only a single location.[4]

In contrast, the results of more recent experiments involving the simultaneous presentation of two or more direct location cues have indicated that single and multiple cueing can facilitate responses to targets presented at cued locations (e.g., Richard, Wright, & Ward, 1996; Wright, 1994; Wright & Richard, 1996; Wright, Richard, & McDonald, 1995, 1996). Perhaps, the critical difference between the two sets of experiments could be *cue type*. When more than one location was symbolically cued at the same time, average response facilitation across trials was weaker than when a single location was symbolically cued. On the other hand, when simultaneous direct cues were presented in our experiments, average response facilitation across trials was roughly equivalent on multiple cue trials (Wright & Richard, 1996).

Are these symbolic cueing and direct cueing results in conflict about the indivisibility of the attentional focal point? In other words, must attention necessarily be divided between two or more locations at the same time in order to account for the multiple direct cueing results? We have argued elsewhere that the answer is no; they do not refute the unitary attentional focal point proposal (e.g., Wright, 1994; Wright & Richard, 1996; Wright, Richard, & McDonald, 1996). In particular, we suggested that a direct location cue appears to affect responses in two ways: (1) its abrupt onset appears to trigger nonattentional sensory processes that facilitate responses, and (2) it enables the attentional focal point to be aligned with its location, thereby allowing attentional processes to facilitate responses. Thus, simultaneous multiple direct cues may trigger sensory-driven (nonattentional) operations that facilitate responses to targets subsequently presented at their locations. This argument has been shaped, in part, by the model proposed by LaBerge and Brown (1989). In short, the symbolic multiple cueing data may reflect alignments of an attentional focal point that is constrained to a single location at any given time. But the results of our direct multiple cueing experiments may reflect the encoding of one or more locations in a *preattentive* manner that is not spatially constrained to a single location in the same way that the attentional focal point is. And, we argue, preattentive encoding of these direct cued locations could have been responsible for roughly equal response facilitation on single vs. multiple cue trials. The key point is that the preattentive encoding of direct cue locations we proposed would have no implications for arguments about the unitary nature of the attentional focal point.

Like many others, we assume that a single attentional focal point can be directed from one location in the visual field to another in a voluntary manner (e.g., in response to the interpretation of symbolic location cues). This is a purely attentive operation. But it is also the case that the visual system must encode locations on the basis of sensory operations that occur prior to the "arrival" of the attentional focal point. If this were not true, then how else could a direct location cue provide a signal to the attentional focal point about where it should go? If location encoding were only possible after some form of attentional processing, then direct cues could not function as triggers for guiding focused attention to their location. Therefore, a processing event that can trigger attentional processing (e.g., location encoding) does not require attentional processing for its own initiation. The spatial locations of such events (e.g., direct cue onsets) must undergo some degree of encoding that is independent of attention. Unlike purely attentive processing, there are fewer spatial constraints on preattentive sensory processing (e.g., Marr, 1982; Neisser, 1964; Treisman & Gelade, 1980). Because our visual system must be capable of encoding locations on the basis of sensory operations, and because these operations are not spatially constrained in the same sense that attentive operations are, preattentive location encoding is possible at more than one location at the same time.

Spatial Indexing and Preattentive Localization

The notion of preattentive location encoding has been implicit in many proposals that are not part of the mainstream attention literature (e.g., Dawson, 1991; Pylyshyn, 1989; Ullman, 1984). They sometimes hold that preattentive operations can be mediated by some form of *spatial indexing* mechanism. In simple terms, indexing is the process by which location information is made available to other visual operations.

The results of several experiments indicate that an index appears to remain "attached" or assigned to objects as they move. As seen in Figure 9, observers in one type of study were shown a number of identical objects (e.g., 10) and asked to keep track of a subset of them. Surprisingly, they could usually track at least four at the same time as the objects moved randomly and independently (Pylyshyn & Storm, 1988;
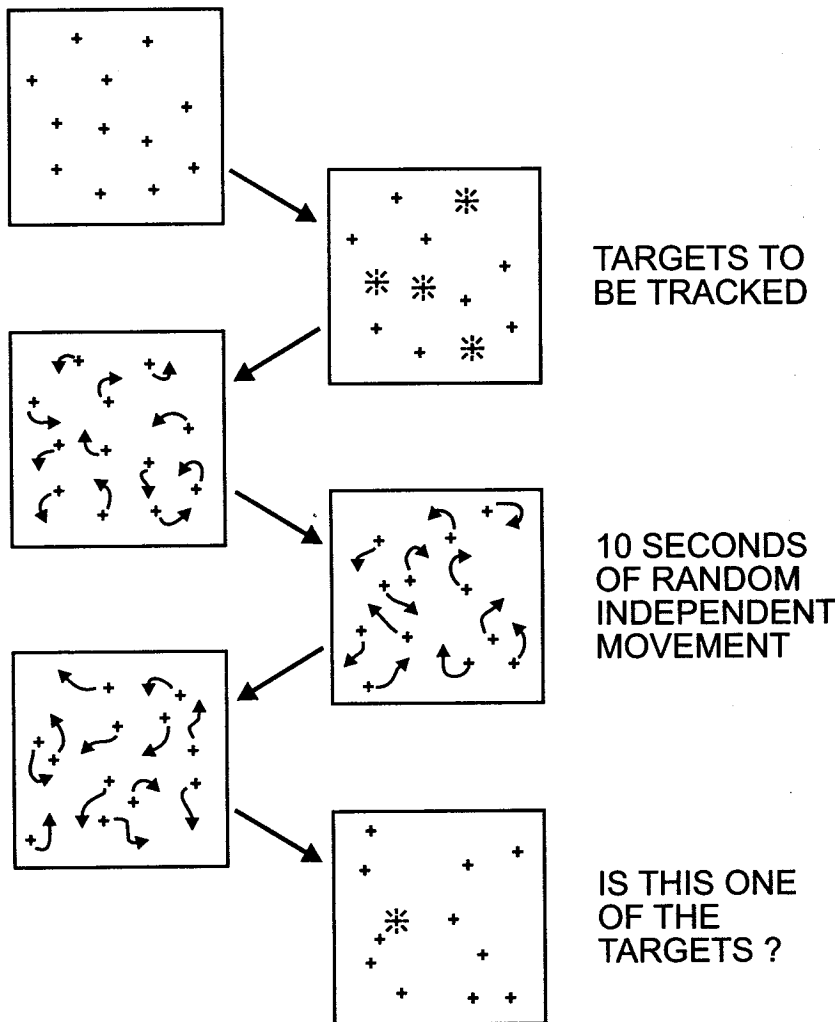
TARGETS TO
BE TRACKED

10 SECONDS
OF RANDOM
INDEPENDENT
MOVEMENT

IS THIS ONE
OF THE
TARGETS ?

Figure 9: Example of the multiple-target tracking task.

Yantis, 1992). Of particular interest is that the high velocity of the objects seemed to preclude the possibility that a serial "scanning and encoding" procedure was used. Instead, tracking appeared to involve a parallel procedure whereby processing was simultaneously directed to each of the four target locations.

Many attention researchers were aware of this finding for several years before it began to influence their work. Part of the reason for this slow acceptance is that high-speed multiple target tracking is difficult to explain in terms of attentional operations. When an observer is asked

to visually track a subset of moving objects, attention seems to be required. On the other hand, the data indicate that tracking several moving objects in parallel is unlikely to be the result of rapid shifts of a single attentional focal point. Therefore, if these data are valid, it is tempting to conclude that the focal point is divisible into multiple attentional foci. In terms of the spotlight metaphor, this is referred to as "splitting the beam of attention." As we have pointed out, however, there is compelling evidence that a single attentional focal point is aligned with different locations in visual space in a serial manner. So if one tried to explain the tracking data in terms of purely attentional processing, the result would be an account that is inconsistent with the current consensus about the unitary nature of the attentional focal point.

Another possible explanation is that while observers must pay attention when performing a tracking task, the maintenance of individual target locations is not due to alignments of focused attention. Perhaps the first clear description of target location encoding that is independent of attention was Ullman's (1984) proposal about *intermediate-level* visual processing. Intermediate-level processing, like low-level sensory processing, is said to be rapid, sometimes parallel, and not always completely available to conscious awareness. On the other hand, it can be influenced and controlled in a goal-driven manner in accordance with the perceptual task that the observer intends to perform (see Figure 10 and Wright & Richard, this volume).[5]

In the case of multiple target tracking, maintenance of target locations by intermediate-level processes would be rapid and parallel. But the initiation of these processes and the selection of the subset of objects to be tracked would be under the observer's control. This is consistent with Ullman's (1984) claim that the intermediate level shares some properties with low-level sensory operations and some properties with high-level cognitive operations. When tracking a subset of four targets, attention is required to control the operation of an intermediate-level tracking procedure; but the encoding of each tracked target's location at any given time is due to a sequence of intermediate-level procedures rather than a series of rapid alignments of a single attentional focal point.

Pylyshyn (1989, this volume) developed an intermediate-level account of high-speed multiple target tracking that was based on a preattentive location-encoding mechanism. In particular, a limited number of indexes (approximately four) were said to be allocated to different objects, and this allocation could be maintained independently of attention as the objects moved. He called these indexes FINSTs for Fingers of INSTantiation. The location information provided by FINSTs is said to be crude. Their primary role when tracking
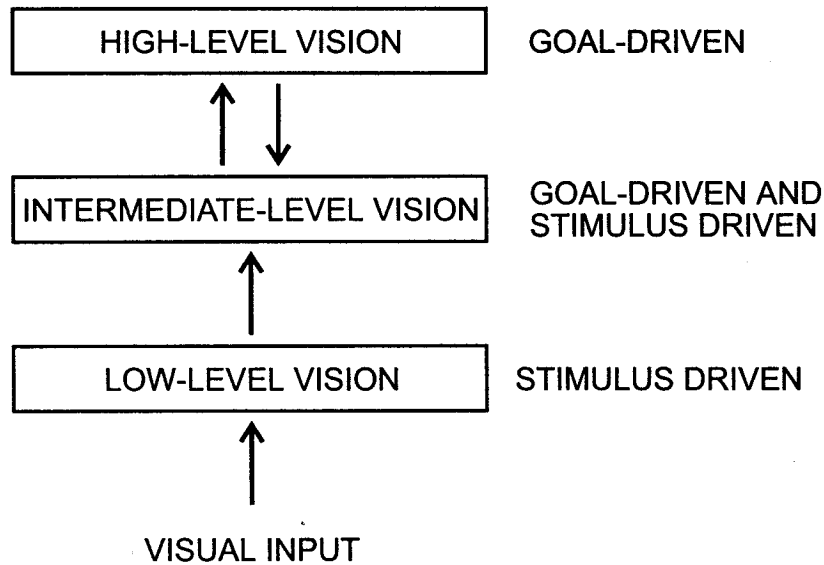
```
┌─────────────────────────────┐
│      HIGH-LEVEL VISION      │        GOAL-DRIVEN
└─────────────────────────────┘
             ↑ ↓
┌─────────────────────────────┐
│  INTERMEDIATE-LEVEL VISION  │        GOAL-DRIVEN AND
└─────────────────────────────┘        STIMULUS DRIVEN
             ↑
┌─────────────────────────────┐
│       LOW-LEVEL VISION      │        STIMULUS DRIVEN
└─────────────────────────────┘
             ↑

          VISUAL INPUT
```

Figure 10: Three levels of visual processing. The intermediate level can be influenced in a goal-driven and a stimulus-driven manner.

targets is simply to stay "glued" to the moving object. If, at some point, the observer is required to verify that a particular object is a target, he can respond on the basis of whether or not the object is indexed. Thus, Pylyshyn's proposal addresses the preattentive maintenance of continually changing location information.

It has also been suggested that a form of spatial indexing is involved in preattentive encoding of objects that suddenly appear in the visual field. Recall that when attention is actively focused or engaged at a particular location, an abrupt onset of an irrelevant stimulus in the visual periphery will *not* "distract" the observer and cause attention to be disengaged and captured at the irrelevant stimulus location (Yantis & Jonides, 1990). But abrupt-onset stimuli appear to maintain some level of enhanced processing at their locations for a brief period of time despite engagement of the attentional focal point elsewhere. And if attention is disengaged within this brief period, a stimulus-driven shift may still be triggered to the location of one of these stimuli (Yantis & Johnson, 1990; Yantis & Jones, 1991). On the basis of their finding that as many as four abrupt-onset stimuli can do this, Yantis and Johnson (1990) proposed that such stimuli generate *interrupt signals* like those sent from peripheral devices to the central processing unit of a computer. If actively focused or engaged attention blocks these signals, they can be temporarily stored in a hierarchical queue or buffer while

attention is engaged. In other words, their locations remain preattentively indexed even while the attentional focal point is unavailable. Müller and Humphreys (1991) developed a similar proposal. Note that, according to these researchers, the maximum number of location interrupt signals generated and temporarily stored in the buffer (four or five) is the same as the number of spatial indexes Pylyshyn and Storm (1988) thought to be available for tracking multiple moving objects.

In our opinion, the primary role of a spatial index is to convey location information. One common misunderstanding about index allocation is the extent to which this operation is thought to cause processing facilitation or inhibition. We suggest that an index serves only to provide subsequent operations with information about its location, and allocation does not facilitate or inhibit subsequent processing there. It is simply a marker for encoding and keeping track of a relevant location. This was Pylyshyn's (1989) motivation for describing spatial indexes as "fingers" that point to locations while attention is elsewhere.

Some of the properties of spatial indexes include the following: (1) there seem to be about four of them; (2) they can remain allocated to objects in a dynamic manner as indicated by the performance of multiple target tracking tasks; (3) they can be allocated in a stimulus-driven manner to the locations of abrupt-onset stimuli and other visual transients, and in a goal-driven manner in accordance with the perceiver's computational goal (e.g., track four objects as they move); (4) signals from indexed locations may be stored in a queue and objects at these locations will be given "attentional priority" in the event that attention becomes disengaged and available for further processing; and (5) indexes are merely markers and do not themselves cause facilitation or inhibition of processing as a result of their allocation at a particular location (see also, Pylyshyn, this volume).

The Activity Distribution Model

The spotlight and zoom lens models described in the previous section were proposed as metaphors of the attentional focal point. They do not, however, describe the sensory-driven events that trigger its alignment with different locations. It is implied that attention is somehow captured by the appearance of a direct location cue or is somehow guided to a symbolically cued location in a voluntary manner. But no account is given of the processes that control alignments of the attentional focal point.

In the 1980s, David LaBerge and his colleagues developed a model to account for goal-driven and stimulus-driven control of attentional alignments (e.g., LaBerge & Brown, 1989). They proposed that preattentive sensory operations lead to the accumulation of "activity

distributions" within representations of the visual field. This is quite a different proposal than its predecessors. In particular, when the analog spotlight metaphor is used to describe a shift of visual attention, this alignment involves a movement component. In contrast, when an activity distribution model is used to describe the shift, no movement occurs. Instead, neural activity is dynamically distributed throughout a representation of the visual field (see Figure 11) and, as visual events occur, activity in neighbouring regions can accumulate to form a number of activation peaks at different locations. When a sufficient amount of activation accumulates at a particular location (e.g., a cued location), a channel of focused attention will open up there.

Advocates of activity distribution models claim that response facilitation produced by valid location cueing is a consequence of a "head start" in the accumulation of activation at the impending target's location. Similarly, they claim that differences in response facilitation produced by differences in the time between cue and target onset arise from differences in the amount of activation that accumulates at the cued location before target onset. At the optimal delay between cue and target onset, the greatest amount of activation is present at the cued location prior to the target's appearance there. Note that these activity distributions are not accumulations of attentional resources and therefore should not be confused with attentional gradient models (e.g., Downing & Pinker, 1985). As seen in Figure 11, neural activation occurs at a preattentive level, and stimulus-driven alignments of focused attention at a particular location are the result of this activation.

The stimulus-driven components of the model initiate the accumulation of neural activation at the represented locations of abrupt-onset stimuli and other visual transients. The goal-driven components determine, in accordance with the observer's computational goals, the chosen represented location at which neural activation accumulates. When either the stimulus-driven or goal-driven accumulation of activation is great enough, a channel of focused attention is opened at that location. Attention, then, is described in a "positive" way as depending on the buildup of activation at the attended site. Note that attention has also been described by others in a "negative" way in terms of buildup of inhibition at unattended sites (e.g., Treisman & Gormican, 1988). This implies that some kind of filter or mask allows only the attended location to be processed because this is the only location with an absence of inhibition. The positive vs. negative distinction is sometimes referred to as "amplification" vs. "filtering" (e.g., Martindale, 1991). There is empirical evidence in favour of both views and LaBerge (1995, this volume; LaBerge & Brown, 1989) proposed that they play complementary roles in attentional alignment and focusing.
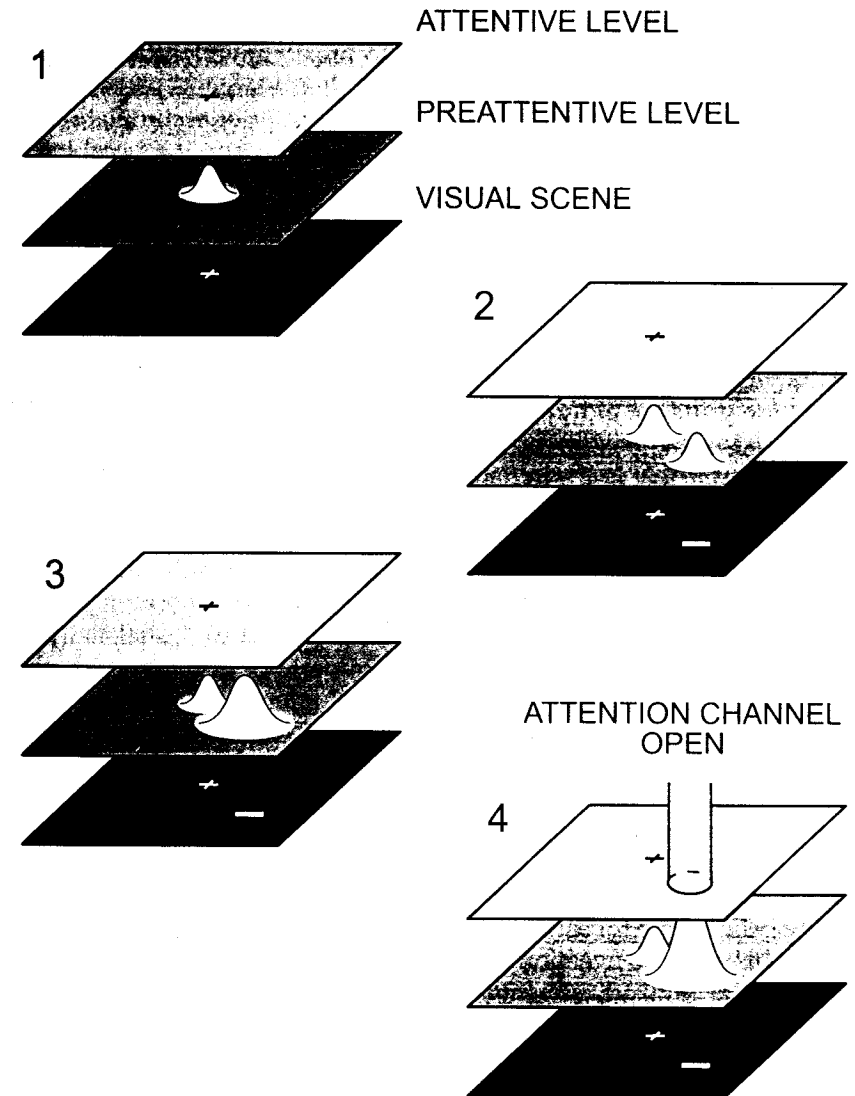

Figure 11: A simplified version of LaBerge and Brown's (1989) activity distribution model. The black surface is the stimulus display, and the grey surface is an intermediate-level representation of it within which activity distributions accumulate. The upper surface is a higher-level representation within which a channel of focused attention can be opened if the accumulation of activity at a particular location exceeds a threshold level. The peaked distributions are a form of preattentive location encoding.

Spatial indexing can also be accounted for by the model because several stimulus onsets can occur at the same time and lead to the accumulation of multiple activity distributions independently of the channel of focused attention. This is tantamount to preattentive location encoding. Response facilitation is said to occur when a target is presented at a location at which there has already been some prior accumulation of neural activation. As seen in Figure 11, this can occur at several locations at the same time. LaBerge and Brown (1989) did not intend their model to fully account for the complex nature of attentional alignments. But theirs was one of the first formal models to suggest how a single indivisible attentional focal point could be aligned in a serial manner with different locations while, at the same time, locations could be encoded preattentively in a parallel sensory-driven manner. In our terms, the model is a possible account of how the destinations of attention shifts are indexed by preattentive localization operations. As discussed in the next section, preattentive destination indexing may play the same role in the initiation of saccadic eye movements.

Visual Attention and Eye Movements

While we are able to shift visual attention independently of eye fixation, there are some situations (e.g., performance of laboratory attention tasks) in which this seems unnatural and effortful. Visual analysis is more efficient if, instead, we pay attention to objects on which our eyes are fixated. Moreover, the locations of attentional focus and eye fixation correspond so frequently that many researchers feel that there must be a close relationship between them.
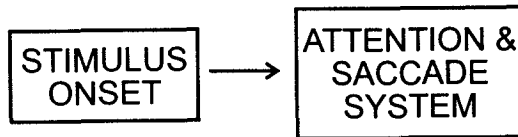
Consider the *orienting reflex* that occurs in most large animals, including humans, to sudden sounds, lights, movements, and other abrupt changes in the perceptual field (see Rohrbaugh, 1984, for a review). This could be a saccade in the direction of an orienting stimulus that results in the foveation of that stimulus and a finer analysis of its object properties. Foveation is an integral part of this reflex, which also includes postural adjustments, and possibly head and body motion toward the stimulus. It is plausible that a mechanism for attentional orienting evolved along with that controlling foveation and the other orienting responses involved in this reflex, several of which are often taken as indicating attending (decreased heart rate, pupil dilation, pause in breathing). Furthermore, the foveating saccades would be nonfunctional if attentional focus were independent of them, since the necessary higher-level processing of the orienting stimulus for meaning would be less likely. Thus, a close relationship between human eye movements and attention shifts may, in part, be a consequence of the evolution of the orienting reflex in our ancestors.

Several researchers have studied this relationship but its details have not been easy to uncover (e.g., Groner & Groner, 1989; Henderson, 1992; Klein, 1980; Posner, 1980; Remington, 1980; Shepard, Findlay, & Hockey, 1986). Experiments conducted to determine whether or not attention precedes a saccadic eye movement to its destination have led to some disagreement. One position is that attention shifts always precede saccades to their destination, and it is implied by some researchers that attention plays a role in eye movement programming (e.g., it may serve as an "advance scout" that relays some form of location information to the saccade mechanism). The opposite position is that while attention shifts and saccades often have a common destination, they are mediated by functionally independent systems and therefore attentional operations are not necessary for saccadic operations and vice versa. Of course not every researcher supports one or the other of these two extreme positions, but it is helpful for reader to know what the positions are when attempting to understand the current debate about the relationship between attention shifts and eye movements.
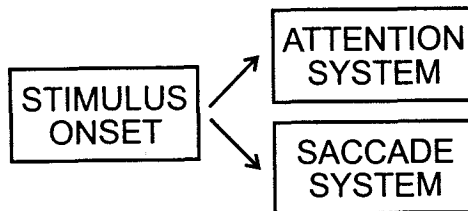
Saccades can be programmed and executed either in a reflexive (stimulus-driven) manner in response to the abrupt onset of a visual stimulus or in a voluntary (goal-driven) manner (e.g., Abrams & Jonides, 1988; Findlay, 1981; Fischer & Weber, 1993; Klein, 1978; Posner, Crippen, Cohen, & Rafal, 1986; Shepard et al., 1986; Todd & Van Gelder, 1979). Readers who are familiar with the eye movement literature may notice that what we call stimulus-driven saccades are sometimes referred to by eye movement researchers as "goal-directed" (e.g., Fischer & Breitmeyer, 1987; Fischer & Weber, 1993). Their use of the term goal-directed is meant to convey that the observer has a basic goal of allowing a saccade to be made to the location of a cue or target. We use the terms stimulus-driven and goal-driven in a way that is consistent with our description of the control of attention shifts. That is, stimulus-driven saccades are triggered by abrupt-onset stimuli whereas goal-driven saccades are voluntarily initiated on the basis of the observer's computational goals (e.g., on the basis of a symbolic location cue's meaning).

Figure 12 shows three models of the possible relationship between attention shifts and eye movements. The first is a unitary-system model. To our knowledge, there is little support for the unitary-system model in a literal sense, but it serves as a useful comparison for the other two models. The second is an "independent-systems" model. Attention and oculomotor operations are carried out independently and share no functional components. The third model is a hybrid of the other two. Some attentional processes are independent of those involved in programming oculomotor movements that adjust eye position. But both

UNITARY SYSTEM MODEL

STIMULUS ONSET → ATTENTION & SACCADE SYSTEM

INDEPENDENT SYSTEMS MODEL

STIMULUS ONSET → ATTENTION SYSTEM / SACCADE SYSTEM

DESTINATION INDEXING MODEL

STIMULUS ONSET → PREATTENTIVE LOCALIZATION → ATTENTION SYSTEM / SACCADE SYSTEM

Figure 12: Three models of the relationship between the attention and saccadic eye movement systems. The upper panel is the unitary system model, the middle panel is the independent systems model, and the lower panel is a hybrid of the other two but with a common destination indexing (preattentive localization) mechanism.

the attentional and saccadic components share a common mechanism that encodes the location of alignment destinations. This is the model we favour. And it has the general structure of the more detailed *destination indexing* model we introduce in the next section.

One proposal that many researchers assume comes close to a claim that eye movements and attention shifts are carried out by the same system is the *premotor theory* of Rizzolatti, Riggio, Dascola, and Umilta (1987). This idea was put forward to explain an attention shift phenomenon sometimes called the "meridian effect." It occurs when detection

response times for invalid-cued targets are inhibited to a greater extent when the cue and target are presented in opposite hemifields (i.e., on opposite sides of the central point in the display) as opposed to in the same hemifield. Rizzolatti et al. (1987) reasoned that detection of same hemifield invalid-cued targets was faster than that of opposite hemifield invalid-cued targets because the attention shift required recalibration for direction in the latter case. They suggested an association of attention with the oculomotor system because a "direction recalibration effect" is known to occur when making successive saccades in different directions. For example, if a saccade is made to a cued location on the right side of the display and then a second saccade is made to a target even further to the right, the latency of the second one will be faster than if the target was in the opposite direction on the left side of the display. More specifically, if the direction component of a saccade must be reprogrammed, this increases the time required before the next saccade can be executed. Therefore, Rizzolatti et al. (1987) reasoned that the meridian effect indicates that, like saccades, changing the direction of two successive attention shifts increases the time required to execute the second shift. On this basis, they concluded that the same calibration procedure is used to program saccades and attention shifts. Taken to the extreme, some researchers have interpreted the proposal of Rizzolatti and colleagues to mean that a single system mediates oculomotor and attentional processes as shown in Figure 12.

One attempt to test this proposal involved a series of direct location-cueing experiments (Crawford & Müller, 1993). The results indicated that attention shift and saccade response-time patterns were qualitatively different. This implies that the operations in the two cases are not identical. But, in fairness to Rizzolatti et al. (1987), it clearly was not their intention to propose that eye movements and visual attention shifts are executed in exactly the same manner. In fact, it would be surprising to find a great degree of similarity between the time-course of these operations because saccade execution involves oculomotor muscle programming and activation that is not required for attention shift execution. Their intended claim seems, instead, to be that calibration of saccades and attention shifts involves a similar procedure.

A counterproposal to premotor theory is the independent-systems model in Figure 12. It yields several predictions including (1) completely independent mechanisms for calibrating saccade and attention shift trajectories, and (2) the eventual discovery of separate brain mechanisms for oculomotor processing and for attentional processing. Based on recent findings, however, it appears that these predictions are too extreme and that oculomotor and attentional processing share common mechanisms.
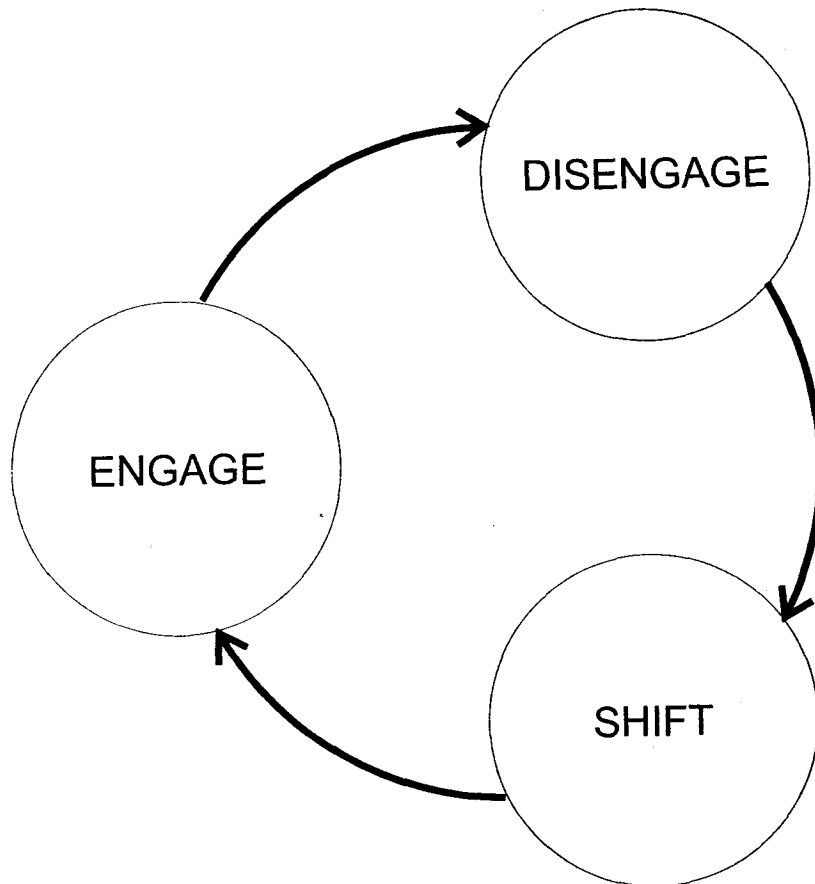
Figure 13: The proposal by Posner et al. (1988) about the disengage/shift/engage sequence of attentional alignment.

Attentional Disengagement and Saccades

Posner et al. (1988) proposed an attention shift model that is similar, in some ways, to a discrete spotlight mechanism (see Figure 5). It involves a sequence in which (1) attention is disengaged before the shift occurs, (2) remains disengaged throughout the shift, and (3) is re-engaged at the shift destination (see Figure 13). This is consistent with reports that attention shifts and saccades will not be triggered by abrupt-onset stimuli if attention is actively engaged at another location (Sparks & Mays, 1983; Yantis & Jonides, 1990).

Saccadic eye movements, like some shifts of visual attention, are discrete. This begs the question "do saccades also undergo the same attentional disengage/shift/engage sequence when they are executed?"

Some researchers have argued that this is not necessarily the case (e.g., Kingstone & Klein, 1993). In their view, disengagement and re-engagement as described by Posner et al. (1988) are attentional operations that have no role in oculomotor processing. But perhaps the relationship between attention and oculomotor systems is closer than this. In particular, there is some evidence that, if attention is in a disengaged state, saccades (Fischer & Weber, 1993) and attention shifts (Mackeben & Nakayama, 1993) can be executed faster than when attention is initially engaged. This implies that both discrete attention shifts and saccades are characterized by the attentional disengage/shift/engage sequence.

Fischer and his colleagues examined the effect of prior attentional engagement on saccade latencies (Fischer, this volume; Fischer & Breitmeyer, 1987; Fischer & Ramsperger, 1984, 1986; Fischer & Weber, 1993). One motivation for doing so was to examine an earlier finding called the *gap effect* (named after the temporal "gap" between fixation point offset and target onset; Saslow, 1967). The time required to initiate a saccade to the location of an abrupt-onset target is about 220 ms when a central fixation point remains visible, but is reduced to about 150 ms when the fixation point disappears shortly before the target's onset. Using a similar procedure, Fischer and others found that when subjects were instructed to fixate their attention on a central point before a peripheral target's onset, saccade latencies were approximately 220 ms. When the fixation point disappeared 200 ms before target onset, however, the latencies of some saccades were closer to 100 ms (e.g., Fendrich, Hughes, & Reuter-Lorenz, 1991; Fischer & Breitmeyer, 1987; Fischer & Ramsperger, 1984, 1986; Fischer & Weber, 1993; Jüttner & Wolf, 1992; Mayfrank, Mobashery, Kimmig, & Fischer, 1986; Reuter-Lorenz, Hughes, & Fendrich, 1991). These are often referred to as *express saccades* because of their relatively short latency.

Fischer and Ramsperger (1984) proposed that if attention is not actively focused when an eye movement target is presented, the latency of the saccade will be reduced. In other words, attentional disengagement was thought to be a precursor to saccade execution and, if an observer's attention is already disengaged prior to saccade preparation, latencies would be shorter (see Figure 14). Thus, express saccades were said to occur because the disappearance of the central point caused attentional disengagement prior to saccade preparation, thereby eliminating one of the steps in the saccade initiation process (see Fischer, this volume; Fischer & Weber, 1993; Munoz & Guitton, 1989).

Saccades to the locations of abrupt-onset targets are called *prosaccades* while those in the opposite direction are called *antisaccades*. If there is a 200 ms gap between fixation cross offset and target onset, express saccades will occur in a prosaccade condition but apparently never in an anti-

THE DISENGAGE/SHIFT/ENGAGE SEQUENCE

ENGAGE ATTENTION
ON CENTRAL
FIXATION CROSS

DISENGAGE ATTENTION
WITH FIXATION CROSS
OFFSET

LOCALIZE ABRUPT-
ONSET STIMULUS AND
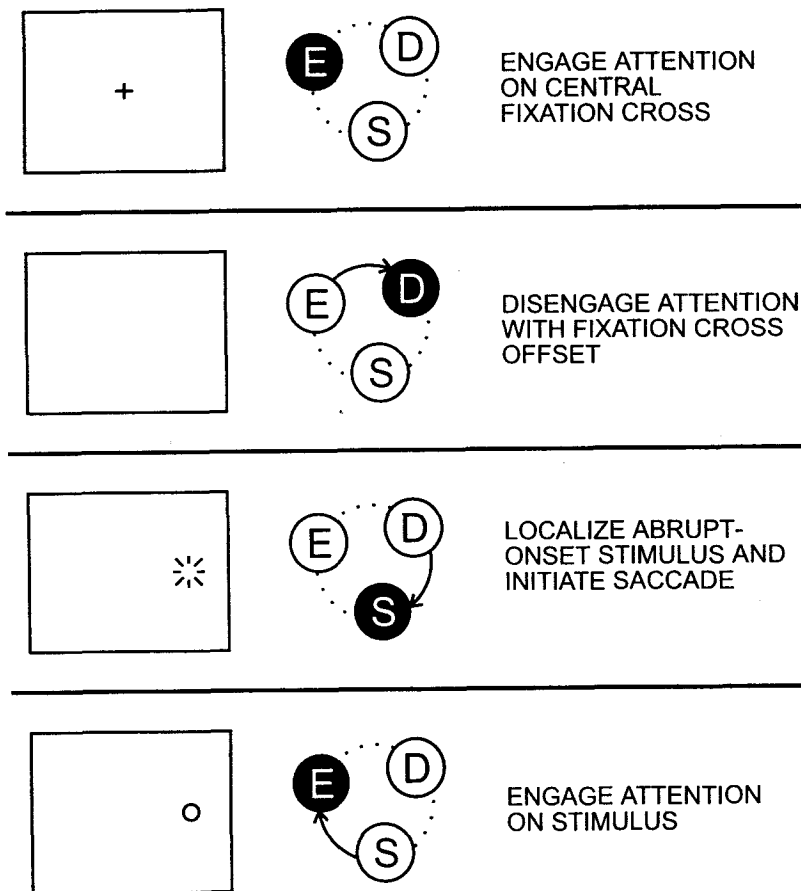INITIATE SACCADE

ENGAGE ATTENTION
ON STIMULUS

Figure 14: The disengage/shift/engage sequence that may occur when observers make express saccades while performing the gap task.

saccade condition (Fischer & Weber, 1992; Reuter-Lorenz, Hughes, & Fendrich, 1991). Presumably, observers can make express prosaccades because, from a state of attentional disengagement, they can allow the saccade target to elicit the saccade directly in a stimulus-driven manner. They are unable to make express antisaccades, however, because they appear to engage attention at the site of the target when it appears (i.e., the target serves as a symbolic cue) and then initiate a goal-driven saccade in the opposite direction. The absence of express antisaccades is another indication that attention is disengaged prior to express saccade execution.

A key property of express saccades is that they are subject to goal-driven and stimulus-driven influences. More specifically, express saccades do not occur if attention is actively focused at any location, including the saccade destination, prior to saccade preparation (Mayfrank et al., 1986). Observers can "override" the occurrence of express saccades, despite the fixation point's offset, simply by engaging their attention in a goal-driven manner. On the other hand, with practice, observers can learn to make express saccades despite the continued presence of the central fixation point or any other object in the direction of gaze (Fischer & Brietmeyer, 1987). They "enable" their occurrence by disengaging attention in a goal-driven manner. But goal-driven control is not necessary for express saccades. Even unpracticed observers who do not voluntarily engage or disengage attention show express saccades as a consequence of the fixation point's offset. Thus, while the frequency of express saccades can be influenced in a goal-driven manner, they are triggered in a stimulus-driven manner as a consequence of a sensory event.

When it was first proposed, the express saccade generated considerable debate among attention researchers (see e.g., Fischer & Weber, 1993). One initial concern was that only a few laboratories had successfully and consistently found them. Another was about whether they constituted a separate and qualitatively different population of saccades with a latency of roughly 100 ms or instead were part of a continuum with latencies ranging from 100 to 160 ms. With the growing number of replications, however, these concerns are subsiding. The debate about express saccades now seems to centre around the role that attention plays in their execution. For example, there is evidence that stimulus offsets lead to rapid saccades, even when these offsets are unattended (Kingstone & Klein, 1993). On this basis, it was suggested that the operations involved in preparing the express saccade must not be attentional. More specifically, the rationale of this suggestion was that if an observer does not pay attention to a particular sensory event, then any subsequent operations triggered by that event cannot be attentional. When applied to express saccades, the reasoning is that an unattended stimulus offset will not trigger attentional disengagement or any other attentional operation. And therefore, so the argument goes, attentional operations do not play a role in the express saccades.

One concern with this reasoning is that the extent to which a particular process is attentional is *not* determined by the nature of the event that triggers it. Recall the earlier discussion about how direct cue onsets guide attention shifts to their locations without requiring prior attentional processing. These onsets are sensory events that trigger attentional events without attention playing a role in the triggering process.

Similarly, stimulus offsets, whether attended to or not, are sensory events. We suggest that the extent to which these sensory events are attended to has no bearing on whether attentional operations play a role in express saccades.

Physiology of Attentional and Oculomotor Processes

Some researchers have suggested that disengagement before eye movements is qualitatively different than disengagement before visual attention shifts (e.g., Klein & Taylor, 1994, p. 134). The latter is said to be an *attentional* operation while the former is said to be an *oculomotor* operation. This leads to an expectation that they should be carried out by separate brain areas. It is becoming apparent, however, that many neural structures play a common role in both attentional and saccadic operations (see e.g., Rafal & Robertson, 1995). Thus, while the independent-systems model implies that attention and eye-movement mechanisms should be physiologically independent, there is now considerable evidence to the contrary.

Some of the brain areas that play a role in both attentional and saccadic operations are the midbrain/collicular structures, the thalamus, the posterior parietal cortex, and the frontal eye fields. Locating and directing saccadic eye movements and attention toward an abrupt-onset stimulus is predominantly under the control of midbrain and superior colliculus (e.g., Wurtz & Albano, 1980). Some neurons in the superior colliculus become very active prior to and during regular saccades, express saccades, and attention shifts (Goldberg & Wurtz, 1972; Rohrer & Sparks, 1986; Wurtz & Mohler, 1976) and electrical stimulation of these neurons will also trigger saccades (Sparks & Mays, 1983). Furthermore, express saccades do not occur if the superior colliculus is damaged (Munoz & Wurtz, 1992; Schiller, Sandell, & Maunsell, 1987), and are not elicited as easily by electrical stimulation of this area when attention is engaged (Sparks & Mays, 1983). It has been suggested that the superior colliculus mediates saccade programming by determining the vector between initial and final eye positions within a map of visual space (Munoz, Pelisson, & Guitton, 1991). There is a general consensus that the primary roles of the superior colliculus are to (1) select the locations of abrupt-onset stimuli and visual transients (Albano, Mishkin, Westbrook, & Wurtz, 1982) and (2) initiate rapid stimulus-driven saccades and attention shifts to these locations (Sparks & Mays, 1980; Wurtz & Albano, 1980).

The posterior parietal cortex is another brain area associated with the control of eye movements and attention shifts (e.g., Petersen, Corbetta, Miezin, & Shulman, 1994). Like the superior colliculus, neural activity in the posterior parietal cortex increases prior to and during saccades

and attention shifts in monkeys (Andersen, Essick, & Siegel, 1985; Bushnell, Goldberg, & Robinson, 1981; Mountcastle, 1978; Robinson, Goldberg, & Stanton, 1978; Wurtz, Goldberg, & Robinson, 1980) and humans (Posner, Walker, Friedrich, & Rafal, 1984, 1987). Damage to the posterior parietal cortex can cause an impairment of eye movements called oculomotor apraxia (Allison, Hurwitz, White, & Wilmot, 1969) and can increase saccade and attention shift latencies in monkeys (Lynch & McLaren, 1989) and humans (Posner et al., 1984, 1987; Sundqvist, 1979).

The frontal eye fields also contain neurons that are active prior to and during saccades as well as neurons that are active after saccade execution (Goldberg & Bushnell, 1981). Some researchers (e.g., Breitmeyer, 1986) have suggested that sustained postsaccadic activity of these neurons may counteract the suppression of visual processing during saccades (cf. Grimes, 1995) so that this suppression does not carry over into the next fixation interval. And the frontal eye fields appear to exert goal-driven control over saccadic eye movements and perhaps attention shifts (e.g., Dassonville, Shlag, & Schlag-Rey, 1992; Guitton, Buchtel, & Douglas, 1985; Henik, Rafal, & Rhodes, 1994; Schiller, True, & Conway, 1979).

The frontal eye field neurons may work in conjunction with the pulvinar nucleus of the thalamus to mediate attentional filtering. Studies of the thalamus indicate that neural activity in the pulvinar increases when humans perform attentional filtering tasks (LaBerge, 1995; LaBerge & Buchsbaum, 1990; Petersen, Robinson, & Morris, 1987) and that this type of performance is impaired as a result of pulvinar damage (Rafal & Posner, 1987). Moreover, the same performance deficits occur when monkey pulvinar functioning is impaired by chemical injections (Petersen, Robinson, & Keys, 1985; see also, LaBerge, 1990b). Thus, the pulvinar appears to be involved in focusing or engaging attention. LaBerge (this volume) has since developed a detailed proposal about the role of the thalamus in attentional processing.

Posner et al. (1988) associated the disengage/shift/engage model in Figure 13 with different brain areas, and proposed that the superior colliculus, posterior parietal cortex, and pulvinar work together as a network to mediate attention shifts. Recent data support this proposal. In particular, the posterior parietal cortex appears to work with the pulvinar to engage and maintain visual fixation and attentional focus, and to work with the superior colliculus to control the initiation of attention shifts and saccades from one location to another. An important but often overlooked point is that the posterior parietal cortex contains many different neurons including some that are involved in disengagement and some that are involved in maintaining engagement (Mountcastle, 1978). Thus, damage to posterior parietal cortex in humans can

disrupt the capacity to disengage attention from an object (e.g., Rafal & Robertson, 1995). But it can also disrupt the capacity to focus attention on a new object (Cohen & Rafal, 1991). Furthermore, some neurons in the monkey posterior parietal cortex are active prior to saccade execution and do not require the presence of a stimulus for their activation (Duhamel, Colby, & Goldberg, 1992). This presaccadic activation could be related to attentional disengagement. In contrast, neighbouring "visual fixation" neurons are active while attention is engaged or focused on a stationary stimulus (Lynch, 1980; Mountcastle, 1978), and express saccades are inhibited when this type of neuron is electrically stimulated (Shibutani, Sakata, & Hyvaerinen, 1986). These results indicate that the posterior parietal cortex is involved in both the maintenance of engaged attention and the disengagement of attention prior to stimulus-driven saccades and attention shifts.

Unlike saccades, smooth pursuit eye movements are not discrete. And, in some cases, focusing attention can even facilitate their execution. Smooth pursuit tracking performance, for example, has been shown to improve when observers focus their attention on a moving target in order to read changing letters or numbers (Shagass, Roemer, & Amadeo, 1976), press a button when the centre of the moving target fills (Iacono & Lykken, 1979), or notice a target colour change (Levin, Lipton, & Holzman, 1981). Moreover, deficits in tracking performance common in schizophrenic patients (Holzman, 1985; Holzman, Proctor, & Hughes, 1973) are attenuated if these patients are required to analyze the target for some type of detail as it moves (Van Gelder, Anderson, Herman, Lebedov, & Tsui, 1990). This suggests that attention remains engaged during smooth pursuit eye movements and that tracking performance deficits are due to attentional disengagement from the target. Therefore, there appears to be a great degree of interdependence between oculomotor and attentional processes.

Destination Indexing

A common experimental procedure is to require a stimulus-driven saccade to the peripheral location of a direct cue. Then, shortly after the cue's onset, a target is presented at the cued location. The purpose is to examine the effects of saccade preparation and execution triggered by the cue's onset on target detection and identification responses. There is a concensus that responses to targets presented at the location of a direct cue are facilitated before, during, and after a stimulus-driven saccade's execution to that destination (Posner, 1980; Remington, 1980). There is less agreement about whether the same pattern of response facilitation occurs when saccades are goal-driven. But the results of one experiment indicated that if a goal-driven eye movement is made in the

same direction as the location of the target to be detected, its preparation will facilitate response times even when the CTOAs are as short as 70 ms (Shepard et al., 1986). At intervals of this duration, saccade preparation is underway but execution requires more time (regular saccade latency is about 220 ms). Therefore, there may be some aspect of saccade *preparation*, even when goal-driven, that facilitates target detection at the saccade destination.

One interpretation of these data is that the attentional focal point precedes the eye movement to its destination. This could explain why responses were facilitated even when targets were presented prior to the saccade. But the eyes are stationary only about 25% of the time and, during some portion of this interval, attention may not even be actively engaged (Fischer & Weber, 1993). Therefore, only a short period of time is actually spent both foveating and focusing attention at a particular location. If the attentional focal point is aligned with each new saccade destination as a sort of "advance scout" (perhaps to send back more precise spatial coordinate information to assist in the saccade trajectory calibration), then this raises questions about how we attend to foveated objects when, as suggested, attention is usually "one step ahead" at the next location to be foveated. It is unlikely that the attentional focal point is split into two "beams" – one for the currently foveated location and one for the next location to be foveated. And if attention is directed to new saccade destinations well before the saccades are executed, this limits the time we spend attending to the locations that are foveated.

One plausible alternative is that, when preparing a saccade, a *spatial index* is allocated to the saccade destination to preattentively encode this location. And focused attention, relieved of the scouting role, can remain at the foveated location to enable analysis of the fixated object in more detail. Note that if indexing is part of saccade preparation, it will occur even if this preparation is followed by suppression of the saccade. This accounts for a visual search finding called *inhibition-of-return* (IOR) that is produced by saccades and attention shifts (Harman, Posner, Rothbart, & Thomas-Thrapp, 1994; Posner & Cohen, 1984; Rafal, Egly, & Rhodes, 1994; Tipper & Weaver, this volume; Wright & Richard, this volume). In particular, stimulus-driven attention shifts can produce IOR in the absence of eye movements, but goal-driven shifts only produce IOR if goal-driven saccades are also made (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985). An important exception to this is when observers make a goal-driven attention shift but merely prepare an accompanying goal-driven saccade without actually making it (Rafal, Calabresi, Brennan, & Sciolto, 1989). The resulting IOR suggests that saccade preparation is sufficient for indexing the saccade destination. And, as mentioned previously, indexing could

mediate attention shifts triggered by direct location cueing (e.g., Wright, 1994; Wright & Richard, 1996). We suggest that the same is true of externally triggered saccades, and that a common *destination-indexing mechanism* initiates both stimulus-driven attention shifts and saccades. This is consistent with the third model in Figure 12 and with the model we describe in the next section.

Cognitive Architecture of Stimulus-Driven Attention Shifts

One of the first brain areas to be studied in detail to determine its role in attentional processing was the reticular activating system (RAS). This research was not a great catalyst to the study of attentional physiology, however, because the RAS findings were difficult to interpret. They implied only that the role of the physiological mechanism underlying attentional processing is to somehow increase our general arousal level. Psychologists began to study the physiology of attention more seriously in the 1980s following a series of findings that separate areas within the cortex appear to be specialized for the processing of colour, form, and motion (e.g., Livingston & Hubel, 1987). Recall that feature-integration theory is based on the assumption that feature information is processed in separate anatomical maps and that focused attention is required at a particular location within a master location map in order for these features to be correctly conjoined to form a perceptual object. Thus, it now seems clear that attentional processing is not a consequence of the operation of a single brain area like the RAS. Instead, it is the product of a network of different brain areas working together cooperatively as suggested by Posner et al. (1988).

The model of Posner et al. (1988), positing a sequence of disengage, shift, engage, can be re-conceptualized so that processing within each module operates on a simple 5 × 5 spatial map. In Figure 15, the upper left map in each set corresponds to the DISENGAGE module, the lower map corresponds to the ENGAGE module, and the middle right map corresponds to the SHIFT module. A chain of events is shown that begins with attention in an engaged state at the centre location within the ENGAGE and DISENGAGE maps. Note, too, that the DISENGAGE module inhibits the SHIFT module (as signified by the line with the closed circle that connects them). In the second event, attention is disengaged and the DISENGAGE module no longer inhibits the SHIFT module. In the third event, a stimulus appears at a location within the SHIFT module map. And finally in the fourth event, the SHIFT module activates the ENGAGE module and begins the process of attentional engagement at the location of the new stimulus. The sequence can begin again but this time with attention focused at the new location on the right side of the ENGAGE and DISENGAGE maps.
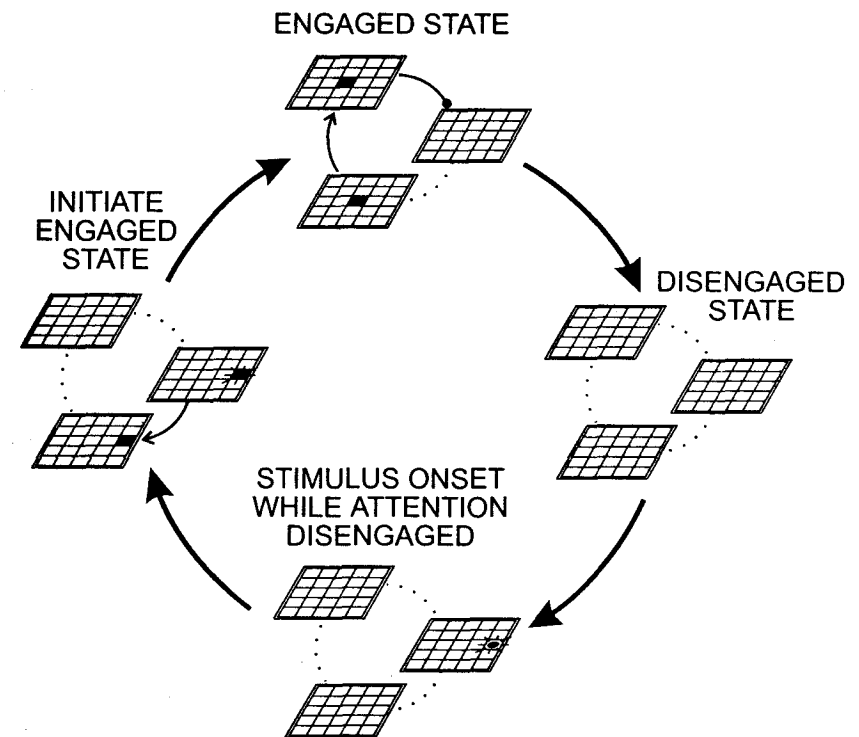
Figure 15: An example of the chain of events associated with the disengage/shift/engage sequence, beginning at the top and moving clockwise. An old stimulus in the centre of the display disappears, and then a new stimulus appears on the right side of the display.

A map-based model has also been used to describe feature integration (Treisman & Gelade, 1980). As shown in Figure 8, information from feature maps is combined within a master map at the location on which attention is focused. These feature maps are very likely located in specialized regions of visual cortex (Treisman & Gormican, 1988). We suggest that the master map in the feature-integration model is similar in function to the DISENGAGE module map in Figure 15. Thus, the two models can be combined as in Figure 16 on the basis of a common master/DISENGAGE map. By doing so, a framework is in place for describing how features are integrated to form objects and how the attentional focal point can be shifted from one location to another within the master map, and particularly in response to an abrupt-onset location cue.

We suggested in the previous section that attention shifts and saccadic eye movements share the same destination indexing operation. In Figure 16, this is carried out by the SHIFT module within the superior colliculus. Stimulus onsets are detected by this module and their
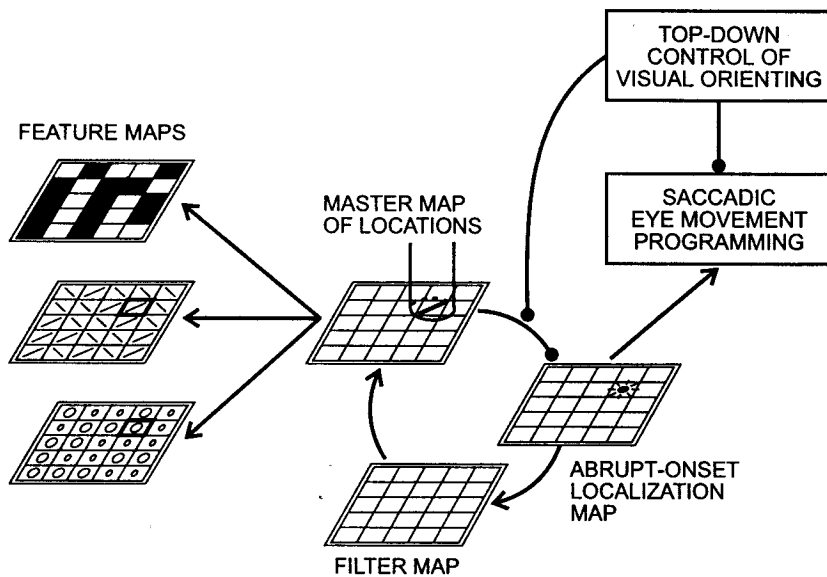
Figure 16: Combining the map-based feature-integration model with the map-based disengage/shift/engage model. The common representation is the master/disengage map. Saccade programming is carried out by the motor cortex module, and goal-driven control of model operations is the result of input from the frontal cortex module.

locations are encoded within its map and made available for attention shift and saccade programming. The latter is shown as occurring within the motor cortex as opposed to within the disengage/shift/engage attention network.

A more specific description of the processing involved when stimulus-driven attention shifts are executed is shown in Figure 17. We call this the *destination-indexing* (DI) system. When one or more abrupt-onset stimuli are presented, the superior colliculus automatically encodes their locations as potential destinations for stimulus-driven saccades and attention shifts, and allocates as many as four indexes (one per stimulus) to their locations. If, at this time, attentive fixation is actively maintained at a particular location (via the frontal lobes), the posterior parietal cortex will inhibit a stimulus-driven shift or saccade. The ability of the stimuli to attract attention persists for a while until it attenuates or until attention is disengaged (see e.g., Müller & Humphreys, 1991; Yantis & Johnson, 1990). Some superior colliculus neurons provide a sustained signal about the locations of stimuli and are thus possibly involved in temporarily "storing" this information (Mays & Sparks, 1980; Peck, Schlag-Rey, & Schlag, 1980). If or when attention is disengaged, the superior colliculus initiates a shift/saccade to the in-
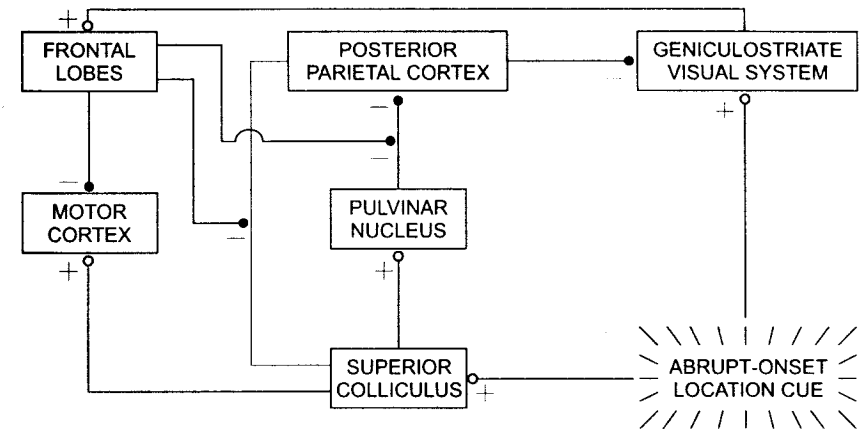

Figure 17: The Destination Indexing model's simplified account of the initiation of stimulus-driven saccadic eye movements and stimulus-driven attention shifts.

dexed stimulus location with the highest priority. After the execution of an attention shift (and a saccade if it is not suppressed) to the indexed location, attention may be re-engaged and actively maintained at this new location through the coordinated actions of the pulvinar and the posterior parietal cortex.

The DI system operates on the assumption that stimulus-driven attention shifts and saccades are triggered by abrupt-onset stimuli but can be temporarily suppressed if attention is currently engaged (Yantis & Jonides, 1990). A key property of the model is that stimulus-driven saccade destination indexing is *not* under voluntary control. Therefore, even if the execution of such a saccade is suppressed, its initial preparation will still be carried out, and this includes selecting the highest priority indexed location as the saccade destination (cf. Yantis & Johnson, 1990). Similarly, the execution of a stimulus-driven attention shift, unless inhibited by attentional engagement, is not under voluntary control. And, even if the shift is inhibited, destination indexing will still occur.

The DI system is similar in some ways to Treisman and Gormican's (1988) proposal in which the processing of unattended locations in visual space is inhibited while attention is focused at a particular location. More specifically, they suggested that "paying attention" occurs when the inhibitory links between the master map and the corresponding locations in the feature maps (e.g., colour, shape, movement, depth) are themselves inhibited. This allows features at the selected location within each feature map to be integrated into a perceptual object (e.g., "a stationary red sphere"). Further integrative processing of the features of all objects at locations not being attended to, however, continues to be inhibited in these feature maps.

Inhibition between modules also occurs in the DI system. As shown in Figure 17, we postulate an inhibitory link from the pulvinar to the posterior parietal cortex and another inhibitory link from the posterior parietal cortex to the superior colliculus. Both links are themselves temporarily inhibited by the frontal lobe when attention is disengaged. When the superior colliculus is freed from inhibition by the posterior parietal cortex in this manner, it can initiate a shift/saccade to the highest priority indexed location. As a result, the corresponding location is facilitated in a map of visual space in the pulvinar which, in turn, releases from inhibition the corresponding location in the posterior parietal cortex map. This produces a release from inhibition by the posterior parietal cortex of the corresponding locations in the feature maps of the geniculostriate system. This amounts to a shift of attention to the indexed location followed by re-engagement at that location when inhibitory links are re-activated (i.e., links from the pulvinar to the posterior parietal cortex and from the posterior parietal cortex to the superior colliculus). At the same time, the superior colliculus also initiates a stimulus-driven saccade to this location unless eye movements are voluntarily suppressed as a result of motor cortex inhibition by the frontal lobes. Thus, when attention is disengaged, selection of an indexed location by the superior colliculus results in a stimulus-driven release from inhibition at the corresponding locations within the feature maps of the geniculostriate system.

Note that the DI system in intended to be a *functional* model, and we emphasize that structural implications should be made with care. For example, long-range inhibitory connections between brain areas may occur only indirectly through the combined action of long-range excitatory pathways to neurons that have short-range inhibitory connections to other neurons in target areas.

The DI model does not describe the processes involved in calibrating attention shift and saccade trajectories, and it does not make explicit the differences between oculomotor muscle programming and attentional alignment operations. In addition, the model does not account for analog attention shifts. Instead it provides a general description of the spatial localization operations involved in selecting shift/saccade destinations and in triggering shifts and saccades to these locations.

Concluding Remarks

This chapter began with a quote by Spearman (1937) about various attempts to characterize attention over years. For quite some time after Spearman's observation, there was a good deal of mystery about the nature of attentional processing. We have argued elsewhere that methodological differences across empirical studies in the literature may have added to this mystery (Wright & Ward, 1994).

In recent years, however, some of the pieces of the puzzle have started to fall into place. Attentional processing appears to be mediated not by a single brain area, but by a network of areas that work cooperatively. Some carry out preattentive analyses of visual feature information, and researchers soon realized that the existence of specialized visual areas must require a master area to integrate their inputs. Treisman and Gelade's (1980) model had a great impact on the field because it developed the notion of location-based feature integration and because it framed the description of attention in terms of spatial maps. Soon after, Posner et al. (1988) concluded, on the basis of considerable physiological evidence, that a network of mechanisms using a disengage/shift/engage sequence appears to align the attentional focal point within a representation of the visual field. When both are described in terms of spatial maps as in Figure 16, the proposals of Treisman and Gelade (1980) and of Posner et al. (1988) are complementary – one describes the alignment of a unitary attentional focal point and the other accounts for the integration of feature information that occurs when this alignment is made with a particular destination. LaBerge (1995, this volume; LaBerge & Brown, 1989) has since proposed a model of stimulus-driven and goal-driven control of these alignments, and Fischer and his colleagues (e.g., Fischer this volume; Fischer & Weber, 1993) elaborated on a possible link between the parietal/collicular interactions involved in attentional disengagement and the collicular/motor-cortex interactions involved in saccadic eye movement programming. Several other researchers, including Pylyshyn (1989, this volume), Yantis (1992; Yantis & Johnson, 1990), and Tipper, Driver and Weaver (1991), developed proposals about visual analyses that involve preattentive encoding of objects and their locations.

When these proposals are taken together, a picture starts to emerge. There appears to be a network of different mechanisms that work together to preattentively encode the destination of visual orienting, to align the attentional focal point and sometimes the eyes with this destination, to selectively attend to a relevant object at the destination, and to integrate the features of that object once attention is engaged.

Acknowledgments

Notes

1　In typical experiments, all cues (symbolic and direct) and targets are abrupt-onset stimuli. This fact is often overlooked. We have omitted the "abrupt-on-set" designation whenever all cues, targets, and other stimuli have an abrupt onset, or whenever the distinction is not important (e.g., when a statement applies to both abrupt-onset and gradual-onset stimuli).

2　The results of visual search experiments also indicate that direct cues are maximally effective at short CTOAs (Nakayama & Mackeben, 1989). When the location of a conjunction target (a target defined by a unique conjunction of the features shared by the distractor items in the search set) was indicated by a direct cue, search accuracy was maximal when the CTOA was 50 ms, but declined when the CTOA was increased to 200 ms.

3　Other evidence that, at longer CTOAs, direct cues can also function as symbolic cues was obtained with a rapid-serial-visual-presentation (RSVP) task (Weichselgartner & Sperling, 1987). A "stream" of numbers was presented at a single display location, one every 80 to 100 ms. When subjects were required to report the first four numbers after direct cue onset, those presented 0 to 100 ms after the cue were reported accurately, effortlessly, and without practice. On the other hand, the next reported numbers were not presented until 300 to 400 ms after the cue, and these reports were effortful, dependent on practice, expectations, the cue's signal-to-noise ratio, and the probability of occurrence of the numbers presented. In other words, reports of the numbers presented 0 to 100 ms after the cue were indicative of the reflexive processes initiated by direct cues at short CTOAs. In contrast, reports of numbers presented 300 to 400 ms after the cue were indicative of the voluntary, effortful processes initiated by symbolic cues at longer CTOAs.

4　Another type of double-cue experiment has also been cited as evidence that attention is directed first to one location and then to the next, rather than being divided between both locations at the same time (Eriksen & Yeh, 1985). It should be noted, however, that each trial involved only a single cue that served as both a direct and a symbolic cue. Therefore, the results of this type of experiment could be due to the different time courses of stimulus-driven and goal-driven attention shifts. As mentioned in the previous section, the effectiveness of symbolic cues at initiating voluntary attention shifts does not appear to be maximal until the CTOA approaches 300 ms (e.g., Cheal & Lyon, 1991; Müller & Findlay, 1988; Shepard & Müller, 1989). Therefore, at the 150 ms CTOA used in this experiment, attention was probably "pulled" to the direct cue location first before being voluntarily shifted to the symbolically cued location. Conclusions about attending to multiple locations that are based on experiments involving symbolic and direct cueing by the same stimulus should therefore be treated with caution. At shorter CTOAs, the results may indicate only that stimulus-driven attention shifts will take precedence over goal-driven shifts.

5　Intermediate-level processing may also be responsible for the automatization of visual search. In particular, both feature targets and highly practiced conjunction targets pop out during visual search. A series of experiments was therefore carried out to determine whether or not the automatized search processes mediating conjunction-target search are the same as those mediating unique-feature target search (Treisman, Vieira, & Hayes, 1992). In general, automatized search was found to be more task-specific and target-location-specific than feature-target search. For example, the possession of a unique feature enabled a target to pop out from distractors during single-target search and the same feature enabled a boundary around a group of these targets to pop out in a texture-segregation task. Conversely, while a conjunction-feature target popped out during single-target search, after extensive practice, the resulting automatization *did not* enable a boundary around a group of these targets to pop out when the texture-segregation task was then performed. This suggests that the pop-out of unique-feature targets is mediated by processes that are more primitive than the ones mediating the automatized popout of conjunction-feature targets. Preattentive analysis of feature information appears to be the result of low-level sensory operations, while automaticity may arise from improved efficiency of intermediate-level operations that become rapid with practice (see also Wright & Richard, this volume).

References

Abrams, R.A., & Jonides, J. (1988). Programming saccadic eye movements. *Journal of Experimental Psychology: Human Perception & Performance, 14,* 428–443.

Albano, J.E., Mishkin, M., Westbrook, J.E., & Wurtz, R.H. (1982). Visuomotor deficits following ablation of monkey superior colliculus. *Journal of Neurophysiology, 48,* 338–351.

Allison, R.S., Hurwitz, L.J., White, J.G., & Wilmot, T.J. (1969). A follow-up study of a patient with Balint's syndrome. *Neuropsychologia, 7,* 319–333.

Andersen, R.A., Essick, G.K., & Seigel, R.M. (1985). Encoding of spatial location by posterior parietal neurons. *Science, 230,* 456–458.

Bonnel, A.M., Possamai, C., & Schmitt, M. (1987). Early modulation of visual input: A study of attentional strategies. *Quarterly Journal of Experimental Psychology, 39,* 757–776.

Breitmeyer, B.G. (1986). Eye movements and visual pattern perception. In E.C. Schwab & H.C. Nusbaum (Eds.), *Pattern recognition by humans and machines, Vol. 2.* Toronto: Academic Press.

Broadbent, D.E. (1958). *Perception and communication.* New York: Pergamon Press.

Bushnell, M.C., Goldberg, M.E., & Robinson, D.L. (1981). Behavioral enhancement of visual responses in monkey cerebral cortex. I. Modulation in posterior parietal cortex related to selective visual attention. *Journal of Neurophysiology, 46,* 755–772.

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

Cohen, A., & Rafal, R.D. (1991). Attention and feature integration: Illusory conjunctions in a patient with a parietal lobe lesion. *Psychological Science, 2,* 106–110.

Crawford, T.J., & Müller, H.J. (1993). Spatial and temporal effects of spatial attention on human saccadic eye movements. *Vision Research, 32,* 293–304.

Dassonville, P., Schlag, J., & Schlag-Rey, M. (1992). The frontal eye field provides the goal of saccadic eye movement. *Experimental Brain Research, 89,* 300–310.

Dawson, M.R.W. (1991). The how and why of what went where in apparent motion: Modeling solutions to the motion correspondence problem. *Psychological Review, 98,* 569–603.

Downing, C.J. (1988). Expectancy and visual-spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology: Human Perception & Performance, 14,* 188–202.

Downing, C.J., & Pinker, S. (1985). The spatial structure of visual attention. In M.I. Posner & O.S.M. Marin (Eds.), *Attention & Performance, Vol. 11.* Hillsdale, N.J.: Erlbaum.

Duhamel, J-R, Colby, C.L., & Goldberg, M.E. (1992). The updating of the representation of visual space in parietal cortex by intended eye movements. *Science, 255,* 90–92.

Egeth, H.E. (1992). Dichotic listening: Long–lived echoes of Broadbent's early studies. *Journal of Experimental Psychology: General, 121,* 124.

Eriksen, C.W., & Colgate, R.L. (1971). Selective attention and serial processing in briefly presented visual displays. *Perception & Psychophysics, 10,* 321–326.

Eriksen, C.W., & Hoffman, J.E. (1974). Selective attention: Noise suppression or signal enhancement? *Bulletin of the Psychonomic Society, 4,* 587–589.

Eriksen, C.W., & Murphy, T.D. (1987). Movement of attentional focus across the visual field: A critical look at the evidence. *Perception & Psychophysics, 42,* 299–305.

Eriksen, C.W., & St. James, J.D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40,* 225–240.

Eriksen, C.W., & Webb, J. (1989). Shifting of attentional focus within and about a visual display. *Perception & Psychophysics, 42,* 175–183.

Eriksen, C.W., Webb, J.M., & Fournier, L.R. (1990). How much processing do nonattended stimuli receive? Apparently very little, but... *Perception & Psychophysics, 47,* 477–488.

Eriksen, C.W., & Yeh, Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception & Performance, 11,* 583–597.

Fendrich, R., Hughes, H.C., & Reuter-Lorenz, P.A. (1991). Fixation-point offsets reduce the latency of saccades to acoustic targets. *Perception & Psychophysics, 50,* 383–387.

Findlay, J.M. (1981). Spatial and temporal factors in the predictive generation of saccadic eye movements. *Vision Research, 21,* 347–354.

Fischer, B., & Breitmeyer, B. (1987). Mechanisms of visual attention revealed by saccadic eye movements. *Neuropsychologia, 25,* 73–83.

Fischer, B., & Ramsperger, E. (1984). Human express-saccades: Extremely short reaction times of goal directed eye movements. *Experimental Brain Research, 57,* 191–195.

Fischer, B., & Ramsperger, E. (1986). Human express-saccades: Effects of daily practice and randomization. *Experimental Brain Research, 64,* 569–578.

Fischer, B., & Weber, H. (1992). Characteristics of "anti" saccades in man. *Experimental Brain Research, 89,* 415–424.

Fischer, B., & Weber, H. (1993). Express saccades and visual attention. *Behavioral & Brain Sciences, 16,* 553–610.

Folk, C.L., Remington, R.W., & Johnston, J.C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception & Performance, 18,* 1030–1044.

Grimes, J. (1995). On the failure to detect changes in scenes across saccades. In K. Akins (Ed.), *Perception.* New York, NY: Oxford University Press.

Goldberg, M.E., & Bushnell, M.C. (1981). Behavioral enhancement of visual responses in monkey cerebral cortex. II. Modulation in frontal eye fields specifically related to saccades. *Journal of Neurophysiology, 46,* 773–787.

Goldberg, M.E., & Wurtz, R.H. (1972). Activity of superior colliculus in behaving monkey. II. Effect of attention on neuronal responses. *Journal of Neurophysiology, 35,* 560–574.

Green, D.M., & Swets, J.A. (1966/1974). *Signal detection theory and psychophysics.* Reprint: New York: Krieger.

Grindley, C.G., & Townsend, V. (1968). Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology, 20,* 11–19.

Groner, R., & Groner, M.T. (1989). Attention and eye movement control: An overview. *European Archives of Psychiatry & Neurological Sciences, 239,* 9–16.

Guitton, D., Buchtel, H.A., & Douglas, R.M. (1985). Frontal lobe lesions in man cause difficulties in suppressing reflexive glances and in generating goal-directed saccades. *Experimental Brain Research, 58,* 455–472.

Harman, C., Posner, M.I., Rothbart, M.K., & Thomas-Thrapp, L. (1994). Development of orienting to locations and objects in human infants. *Canadian Journal of Experimental Psychology, 48,* 301–318.

Henderson, J.M. (1992). Visual attention and eye movement control during reading and picture viewing. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading.* New York: Springer-Verlag.

Henik, A., Rafal, R., & Rhodes, D. (1994). Endogenously generated and visually guided saccades after lesions of the human frontal eye fields. *Journal of Cognitive Neuroscience, 6,* 400–411.

Holzman, P.S. (1985). Eye movement dysfunctions and psychoses. *International Review of Neurobiology, 27,* 179–205.

Holzman, P.S., Proctor, L.R., & Hughes, D.N. (1973). Eye tracking patterns in schizophrenia. *Science, 181,* 179–181.

Iacono, W.G., & Lykken, D.T. (1979). Electrooculographic recording and scoring of smooth pursuit and saccadic eye tracking: A parametric study using monozygotic twins. *Psychophysiology, 16,* 94–107.

James, W. (1890). *Principles of psychology,* Volumes 1 & 2. New York: Holt.

Jonides, J. (1980). Towards a model of the mind's eye's movement. *Canadian Journal of Psychology, 34*, 103–112.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J.B. Long & A.D. Baddeley (Eds.), *Attention & Performance, Vol. 9*. Hillsdale, NJ: Erlbaum.

Jonides, J. (1983). Further towards a model of the mind's eye's movement. *Bulletin of the Psychonomic Society, 21*, 247–250.

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

Jüttner, M., & Wolf, W. (1992). Occurrence of human express saccades depends on stimulus uncertainty and stimulus sequence. *Experimental Brain Research, 89*, 678–681.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.

Kiefer, R.J., & Siple, P. (1987). Spatial constraints on the voluntary control of attention across visual space. *Canadian Journal of Psychology, 41*, 474–489.

Kingstone, A., & Klein, R.M. (1993). Visual offsets facilitate saccade latency: Does pre-disengagement of visuo-spatial attention mediate this gap effect? *Journal of Experimental Psychology: Human Perception & Performance, 19*, 1251–1265.

Klein, R. (1978). Chronometric analysis of saccadic eye movements: Reflexive and cognitive control. In D. Landers & R. Christina (Eds.), *Psychology of motor behavior and sport*. Champaign, IL: Human Kinetics.

Klein, R. (1980). Does ocular motor readiness mediate cognitive control of visual attention? In R.S. Nickerson (Ed.), *Attention & Performance, Vol. 8*. Hillsdale, NJ: Erlbaum.

Klein, R.M., & Taylor, T.L. (1994). Categories of cognitive inhibition with reference to attention. In D. Dagenbach & T. Carr (Eds.), *Inhibitory processes in attention, memory, and language*. Orlando, FL: Academic Press.

Kröse, B.J.A., & Julesz, B. (1989). The control and speed of shifts of attention. *Vision Research, 29*, 1607–1619.

Kwak, H., Dagenbach, D., & Egeth, H. (1991). Further evidence for a time-independent shift of the focus of attention. *Perception & Psychophysics, 49*, 473–480.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception & Performance, 9*, 371–379.

LaBerge, D. (1990a). Attention. *Psychological Science, 1*, 156–162.

LaBerge, D. (1990b). Thalamic and cortical mechanisms of attention suggested by recent positron emission tomographic experiments. *Journal of Cognitive Neuroscience, 2*, 358–372.

LaBerge, D. (1995). *Attentional processing*. Cambridge, MA: Harvard University Press.

LaBerge, D., & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review, 96*, 101–124.

LaBerge, D., & Buchsbaum, M.S. (1990). Positron emission tomographic measurements of pulvinar activity during an attention task. *Journal of Neuroscience, 10*, 613–619.

Lappin, J.S., & Uttal, W.R. (1976). Does prior knowledge facilitate the detection of visual targets in random noise? *Perception & Psychophysics, 20*, 367–374.

Levin, S., Lipton, R.B., & Holzman, P.S. (1981). Pursuit eye movements in psychopathology: Effects of target characteristics. *Biological Psychiatry, 16*, 255–267.

Livingston, M.S., & Hubel, D.H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience, 7*, 3416–3468.

Luria, A.R. (1973). *The working brain*. New York: Penguin.

Lynch, J.C. (1980). The functional organization of the posterior parietal association cortex. *Behavioral & Brain Sciences, 2*, 485–499.

Lynch, J.C., & McLaren, J.W. (1989). Deficits of visual attention and saccadic eye movements after lesions of parietooccipital cortex in monkeys. *Journal of Neurophysiology, 61*, 74–90.

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

Marr, D. (1982). *Vision*. New York, NY: Freeman.

Martindale, C. (1991). *Cognitive psychology: A neural network approach*. Pacific Grove, CA: Brooks/Cole.

Mayfrank, L., Mobashery, M., Kimmig, H., & Fischer, B. (1986). The role of fixation and visual attention on the occurrence of express saccades in man. *European Journal of Psychiatry & Neurological Science, 235*, 269–275.

Mays, L.E., & Sparks, D.L. (1980). Dissociation of visual and saccade-related responses in superior colliculus neurons. *Journal of Neurophysiology, 43*, 207–232.

McCormick, P.A., & Klein, R. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologica, 75*, 225–242.

Mertens, J.J. (1956). Influence of knowledge of target location upon the probability of observations of peripherally observable test flashes. *Journal of the Optical Society of America, 46*, 1069–1070.

Milner, P. (1974). A model for visual shape recognition. *Psychological Review, 81*, 521–535.

Mountcastle, V.B. (1978). Brain mechanisms for directed attention. *Journal of the Royal Society of Medicine, 71*, 14–28.

Mowrer, O.H. (1941). Preparatory set (expectancy): Further evidence for its "central" locus. *Journal of Experimental Psychology, 28*, 116–133.

Müller, H.J. (1994). Qualitative differences in response bias from spatial cueing. *Canadian Journal of Experimental Psychology, 48*, 218–241.

Müller, H.J., & Findlay, J.M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica, 69*, 129–155.

Müller, H.J., & Humphreys, G.W. (1991). Luminance-increment detection: Capacity-limited or not? *Journal of Experimental Psychology: Human Perception & Performance, 17*, 107–124.

Müller, H.J., & Rabbitt, P.M.A. (1989). Reflexive and voluntary orienting of visual attention: Time course activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception & Performance, 15*, 315–330.

Munoz, D.P., & Guitton, D. (1989). Fixation and orientation control by the tecto-reticulo-spinal system in the cat whose head is unrestrained. *Revue Neurologique, 145*, 567–579.

Munoz, D.P., Pelisson, D., & Guitton, D. (1991). Movement of neural activity on the superior colliculus motor map during gaze shifts. *Science, 251,* 1358–1360.

Munoz, D.P., & Wurtz, R.H. (1992). Role of the rostral superior colliculus in active visual fixation and execution of express saccades. *Journal of Neurophysiology, 67,* 1000–1002.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 11,* 1631–1647.

Navon, D. (1989). The importance of being visible: On the role of attention in a mind viewed as an anarchic intelligence system. I. Basic tenets. *European Journal of Psychology, 1,* 191–213.

Neisser, U. (1964). Visual search. *Scientific American, 210,* 94–102

Neisser, U. (1967). *Cognitive psychology.* New York: Appleton, Century, Crofts.

Neisser, U. (1976). *Cognition and reality.* San Francisco: W.H. Freeman.

Peck, C.K., Schlag-Rey, M., & Schlag, J. (1980). Visuo-oculomotor properties of cells in the superior colliculus of the alert cat. *Journal of Comparative Neurology, 194,* 97–116.

Petersen, S.E, Corbetta, M., Miezin, F.M., & Shulman, G.L. (1994). PET studies of parietal involvement in spatial attention: Comparison of different task types. *Canadian Journal of Experimental Psychology 48,* 319–338.

Petersen, S.E., Robinson, D.L., & Keys, J. (1985). Pulvinar nuclei of the behaving rhesus monkey: Visual responses and their modulation. *Journal of Neurophysiology, 54,* 867–886.

Petersen, S.E., Robinson, D.L., & Morris, J.D. (1987). Contributions of the pulvinar to visual spatial attention. *Neuropsychologia, 25,* 97–105.

Posner, M.I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

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

Posner, M.I., & Cohen, Y. (1984). Components of visual attention. In H. Bouma & D.G. Bouhuis (Eds.), *Attention & Performance, Vol. 10.* Hillsdale, NJ: Erlbaum.

Posner, M.I., Cohen, Y., & Rafal, R.D. (1982). Neural systems control of spatial orienting. *Philosophical Transactions of the Royal Society of London, B298,* 187–198.

Posner, M.I., Crippen, P.J., Cohen, A., & Rafal, R. (1986, November). *Speed of covert orienting of attention and express saccades.* Paper presented at the annual meeting of the Psychonomic Society, New Orleans.

Posner, M.I., Nissen, M.J., & Ogden, W.C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H.L. Pick & I.J. Saltzman (Eds.), *Modes of perceiving and processing information.* Hillsdale, NJ: Erlbaum.

Posner, M.I., Petersen, S.E., Fox, P.T., & Raichle, M.E. (1988). Localization of cognitive operations in the human brain. *Science, 240,* 1627–1631.

Posner, M.I., Rafal, R.D., Choate, L., & Vaughan, J. (1985). Inhibition of return: Neural basis and function. *Cognitive Neuropsychology, 2,* 211–218.

Posner, M.I., & Snyder, C.R.R. (1975). Facilitation and inhibition in the processing of signals. In P.M.A. Rabbitt & S. Dornic (Eds.), *Attention & Performance, Vol. 5.* Hillsdale, N.J.: Erlbaum.

Posner, M.I., Snyder, C.R.R., & Davidson, B.J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109,* 160–174.

Posner, M.I., Walker, J.A., Friedrich, F.J., & Rafal, R.D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience, 4,* 1863–1874.

Posner, M.I., Walker, J.A., Friedrich, F.J., & Rafal, R.D. (1987). How do the parietal lobes direct covert attention? *Neuropsychologia, 25,* 135–146.

Possamai, C., & Bonnel, A.M. (1991). Early modulation of visual input: Constant versus varied cueing. *Bulletin of the Psychonomic Society, 29,* 323–326.

Pylyshyn, Z. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition, 32,* 65–97.

Pylyshyn, Z., & Storm, R.W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3,* 179–197.

Rafal, R.D., Calabresi, P.A., Brennan, C.W., & Sciolto, T.K. (1989). Saccade preparation inhibits reorienting to recently attended locations. *Journal of Experimental Psychology: Human Perception & Performance, 15,* 673–685.

Rafal, R.D., Egly, R., & Rhodes, D. (1994). Effects of inhibition of return on voluntary and visually guided saccades. *Canadian Journal of Experimental Psychology, 48,* 284–300.

Rafal, R.D., & Posner, M.I. (1987). Deficits in human visual spatial attention following thalamic lesions. *Proceedings of the National Academy of Science of the USA, 84,* 7349–7353.

Rafal, R.D., & Robertson, L. (1995). The neurology of attention. In M. Gazzaniga (Ed.), *The cognitive neurosciences.* Cambridge, MA: MIT Press.

Remington, R. (1980). Attention and saccadic eye movements. *Journal of Experimental Psychology: Human Perception & Performance, 6,* 726–744.

Remington, R., & Pierce, L. (1984). Moving attention: Evidence for time-invariant shifts of visual selective attention. *Perception & Psychophysics, 35,* 393–399.

Reuter-Lorenz, P.A., & Fendrich, R. (1992). Oculomotor readiness and covert orienting: Differences between central and peripheral precues. *Perception & Psychophysics, 52,* 336–344.

Reuter-Lorenz, P.A., Hughes, H.C., & Fendrich, R. (1991). The reduction of saccadic latency by prior offset of the fixation point: An analysis of the gap effect. *Perception & Psychophysics, 49,* 167–175.

Richard, C.M., Wright, R.D., & Ward, L.M. (1996). *Separate sensory-driven and goal-driven effects of cue onsets in visual space.* Paper presented at the annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science, Montreal, Quebec.

Rizzolatti, G., Riggio, L., Dascola, I., & Umilta, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favour of a premotor theory of attention. *Neuropsychologia, 25,* 31–40.

Robinson, D.L., Goldberg, M.E., & Stanton, G.B. (1978). Parietal association cortex in the primate: Sensory mechanisms and behavioral modulations. *Journal of Neurophysiology, 41,* 910–932.

Rohrbaugh, J.W. (1984). The orienting reflex: Performance and central nervous system manifestations. In R. Parasuramen & D.R. Davies (Eds.), *Varieties of attention.* Orlando, FL: Academic Press.

Rohrer, W.H., & Sparks, D.L. (1986). Role of the superior colliculus in the initiation of express saccades. *Investigative Ophthalmology & Visual Science, 271,* 156.

Sagi, D., & Julesz, B. (1985). Fast noninertial shifts of attention. *Spatial Vision, 1,* 141–149.

Saslow, M.G. (1967). Effects of components of displacement-step stimuli upon latency of saccadic eye movement. *Journal of the Optical Society of America, 57,* 1024–1029.

Schiller, P.H., Sandell, J.H., & Maunsell, J.H.R. (1987). The effect of frontal eye field and superior colliculus lesions on saccadic latencies in the rhesus monkey. *Journal of Neurophysiology, 57,* 1033–1049.

Schiller, P.H., True, S.D., & Conway, J.L. (1979). Effects of frontal eye field and superior colliculus ablations on eye movements. *Science, 206,* 590–592.

Schneider, W., Dumais, S.T., & Shiffrin, R.M. (1984). Automatic and controlled processing and attention. In R. Parasuraman & D.R. Davies (Eds.), *Varieties of attention.* Orlando, FL: Academic Press.

Shagass, C., Roemer, R., & Amadeo, M. (1976). Eye tracking performance and engagement of attention. *Archives of General Psychiatry, 33,* 121–125.

Shaw, M.L. (1983). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention & Performance, Vol. 10.* Hillsdale, NJ: Erlbaum.

Shepard, M., & Müller, H.J. (1989). Movement versus focusing of visual attention. *Perception & Psychophysics, 46,* 146–154.

Shepard, M., Findlay, J.M., & Hockey, R.J. (1986). The relationship between eye movements and spatial attention. *Quarterly Journal of Experimental Psychology, 38A,* 475–491.

Shepard, R.N. (1975). Form, formation, and transformations of internal representations. In R.L. Solso (Ed.), *Information processing and cognition: The Loyola symposium.* Hillsdale, NJ: Erlbaum.

Shibutani, H., Sakata, H., & Hyvaerinen, J. (1986). Saccade and blinking evoked by microstimulation of the posterior parietal association cortex of the monkey. *Experimental Brain Research, 55,* 1–8.

Shulman, G.L., Remington, R.W., & McLean, J.P. (1979). Moving attention through visual space. *Journal of Experimental Psychology: Human Perception & Performance, 5,* 522–526.

Skelton, J.M., & Eriksen, C.W. (1976). Spatial characteristics of selective attention in letter matching. *Bulletin of the Psychonomic Society, 7,* 136–138.

Solso, R.L. (1991). *Cognitive psychology.* Boston, MA: Allyn & Bacon.

Sparks, D.L., & Mays, L.E. (1980). Movement fields of saccade-related burst neurons in the monkey superior colliculus. *Brain Research, 190,* 39–50.

Sparks, D.L., & Mays, L.E. (1983). Spatial localization of saccade targets: I. Compensation for stimulus-induced perturbations in eye position. *Journal of Neurophysiology, 49,* 45–63.

Spearman, C. (1937). *Psychology down the ages.* London: Macmillan.

Sundqvist, A. (1979). Saccadic reaction time in parietal lobe dysfunction. *Lancet, 1,* 870.

Tipper, S., Driver, J., & Weaver, B. (1991). Object-centred inhibition of return of visual attention. *Quarterly Journal of Experimental Psychology, 43*(A), 289–298.

Titchener, E.B. (1910). *A textbook of psychology.* New York: Macmillan.

Todd, J.T., & Van Gelder, P. (1979). Implications of a transient-sustained dichotomy for the measurement of human performance. *Journal of Experimental Psychology: Human Perception & Performance, 5,* 625–638.

Treisman, A. (1964). Selective attention in man. *British Medical Journal, 20,* 12–16.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95,* 15–48.

Treisman, A, Vieira, A., & Hayes, A. (1992). Automaticity and preattentive processing. *American Journal of Psychology, 105,* 341– 362.

Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception & Performance, 9,* 523–530.

Ullman, S. (1984). Visual routines. *Cognition, 18,* 97–159.

Van Gelder, P., Anderson, S., Herman, E., Lebedev, S., & Tsui, W.H. (1990). Saccades in pursuit eye tracking reflect motor attention processes. *Comprehensive Psychiatry, 31,* 253–260.

Ward, L.M. (1985). Covert focusing of the attentional gaze. *Canadian Journal of Psychology, 39,* 546–563.

Ward, L.M. (1994). Supramodal and modality-specific mechanisms for stimulus-driven shifts of auditory and visual attention. *Canadian Journal of Experimental Psychology, 48,* 242–259.

Warren, R.M., & Warren, R.P. (1968). *Helmholtz on perception: Its physiology and development.* New York: Wiley.

Weichselgartner, E., & Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science, 238,* 778–780.

Wright, R.D. (1994). Shifts of visual attention to multiple simultaneous location cues. *Canadian Journal of Experimental Psychology, 48,* 205–217.

Wright, R.D., & Richard, C.M. (1993). *Inhibition-of-return of visual attention to multiple location cues.* Paper presented at the annual meeting of the Psychonomic Society, Washington, D.C.

Wright, R.D., & Richard, C.M. (1994). *Inhibition-of-return to successively and sequentially cued locations.* Paper presented at the annual meeting of the Psychonomic Society, St. Louis, Missouri.

Wright, R.D., & Richard, C.M. (1996). *The effects of simultaneous location cueing at multiple locations in visual space.* Manuscript in preparation.

Wright, R.D., Richard, C.M., & McDonald, J.J. (1995). Neutral location cues and cost/benefit analysis of visual attention shifts. *Canadian Journal of Experimental Psychology, 49,* 540–548.

Wright, R.D., Richard, C.M., & McDonald, J.J. (1996). *Simultaneous sensory-driven effects of cue-onset at multiple locations in visual space.* Paper presented at the annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science, Montreal, Quebec.

Wright, R.D., & Ward, L.M. (1993). Indexing and the control of express saccades. *Behavioral & Brain Sciences, 16,* 494–495.

Wright, R.D., & Ward, L.M. (1994). Shifts of visual attention: An historical and methodological overview. *Canadian Journal of Experimental Psychology, 48,* 151–166.

Wurtz, R.H., & Albano, J.E. (1980). Visual-motor function of the primate superior colliculus. *Annual Review of Neuroscience, 3,* 189–226.

Wurtz, R.H., Goldberg, M.E., & Robinson, D.L. (1980). Behavioral modulation of visual responses in the monkey: Stimulus selection for attention and movement. *Progress in Psychobiology and Physiological Psychology, 9,* 43–83.

Wurtz, R.H., & Mohler, C.W. (1976). Organization of monkey superior colliculus: Enhanced visual response of superficial layer cells. *Journal of Neurophysiology, 39,* 745–765.

Yantis, S. (1988). On analog movements of visual attention. *Perception & Psychophysics, 43,* 203–206.

Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology, 24,* 295–340.

Yantis, S., & Johnson, D.N. (1990). Mechanisms of attentional priority. *Journal of Experimental Psychology: Human Perception & Performance, 16,* 812–825.

Yantis, S., & Jones, E. (1991). Mechanisms of attentional selection: Temporally modulated priority tags. *Perception & Psychophysics, 50,* 166–178.

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

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal Experimental Psychology: Human Perception & Performance, 16,* 121–134.