

**SIMULTANEOUS RESPONSE FACILITATION AT
MULTIPLE LOCATIONS IN VISUAL SPACE**

by

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ABSTRACT

When a target detection task is performed, a visual cue (direct cue) appearing at a potential target position prior to a target onset produces faster mean detection times for targets at cued positions than for targets at uncued positions. This difference is called *cue effects*. Cue effects have been described as being mediated by purely attentive visual operations. Another explanation is that, along with visual attention, sensory activity generated by direct cue onsets may increase perceptual sensitivity and speed of processing at cued locations. These two accounts differ in that attention-related cue effects seems to be confined to a single contiguous region of visual space while sensory-related cue effects may occur at several locations in parallel.

Experiment 1 was designed to test which of these proposals was more appropriate by determining whether or not cue effects can occur at more than one location at a time. One, two, three, or four cues simultaneously appeared 100 ms before the target onset and target-detection response times were measured. The results were more consistent with the proposal that both sensory and attentive processes can contribute cue effects. The purpose of Experiment 2 was to directly measure the simultaneous occurrence of sensory-related and attention-related cue effects in the same cueing display. Three grey direct cues and one red direct cue appeared 100 ms before the target in a detection task. The target occurred at the red-cue location on 66.7% of the trials, giving observers an incentive to attend to that location. Cue effects were observed in the grey-cue condition suggesting that sensory cue effects were activated at multiple locations, while significantly larger cue effects were observed in the red-cue condition

suggesting that attention-related cue effects may have occurred at this location.

Experiment 3 was designed to measure how cue effects change over time. Four cues appeared at different intervals (100, 200, & 300 ms) prior to the target onset. Cue effects only occurred in the 100 ms condition suggesting that cue effects were transient. In sum, this research is consistent with the idea that cue effects following direct cues may involve an interaction between sensory and attentive facilitation operations, which contrasts with other ideas that these processes function independently.

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SIMULTANEOUS CUE EFFECTS AT MULTIPLE LOCATIONS IN VISUAL SPACE

When observers view a real-world scene, they are often confronted with a dynamic visual array containing simultaneous activity at several locations. They might see movement in some areas and, at the same time, the appearance and disappearance of objects in other regions. These events could make analysis of visual information difficult if it were not for an observer's ability to selectively process some areas more than others. In other words, observers seem to explore visual scenes by examining specific regions instead of by examining the entire visual field simultaneously. The procedure by which visual processing is concentrated at a certain location is known as visual attention and it seems to involve enhanced information extraction at the location in question. This enhancement is often reflected by faster response times in target-detection tasks (e.g., Posner, 1980) and by improved accuracy in target-identification tasks (e.g., Cheal & Lyon, 1991a). Thus, visual attention seems to facilitate information processing in the visual field.

The locus of attention in visual space usually coincides with the foveated region of the visual field, but it is also possible to attend to locations independently of the foveal representation as implied by the expression "to look out of the corner of your eye." Helmholtz conducted one of the first controlled demonstrations of this ability over 100 years ago (see Warren & Warren, 1968). He arranged a darkened display of letters around a small lighted pinhole. When a brief spark illuminated the

display, Helmholtz was unable to perceive any of the letters when his eyes were fixated on the pinhole. By concentrating on a certain area before the spark occurred, however, Helmholtz found that he could identify the letters in that region even though his eyes remained on the pinhole. Therefore, by voluntarily shifting his attention away from the foveated location, Helmholtz was able to process information more accurately at peripheral visual locations.

Attention shifts independent of eye movements have been studied extensively in many recent investigations. Shifting attention in this manner has been called *covert orienting* because an observer has no way of determining if or when someone has shifted his or her attention from one location to another (Posner, 1980). Even though an observer's overt behaviour may not reveal the currently attended location, researchers can still measure changes in the locus of attention indirectly by measuring changes in detection response times (e.g., Posner, 1980) or identification accuracy (e.g., Cheal & Lyon, 1991a) for targets appearing at various locations in the visual field. In particular, because visual attention seems to be associated with enhanced visual processing, researchers typically assume that targets appearing at attended locations are detected faster or identified more accurately than targets appearing at unattended locations (e.g., Posner, 1980). Thus, the locus of attention can be indicated by the location in the visual field that yields the fastest and most accurate target responses. In most covert-orienting experiments, researchers try to direct an observer's attention to specific locations in visual space with a cue. A cue is usually a visual stimulus indicating a potential target location prior to the target onset that observers can use to shift their attention to the appropriate location before the target

appears. In this way, researchers can measure the effects of attending to certain locations on target responses.

Cues can be categorized according to how the information they convey relates to the actual target-onset location. More precisely, if a target appears at the same position as indicated by the cue, then that cue provides correct target information and is called is a *valid cue*. In contrast, if a target appears at a location other than the one indicated by the cue, then that cue provides incorrect target information and is called an *invalid cue*. Along with location information, valid and invalid cues also provide temporal warning information. This is a consequence of a cue's onset before the target appears. That is, a cue onset signals an impending target onset. In experiments that compare the effects of valid and invalid cues, it is often necessary to separate the effects of location and temporal warning information. This can be done with a third type of cue called a *neutral cue* that provides a temporal warning but no target-location information. More specifically, a neutral cue would appear at the same time before the target as a valid or an invalid cue but would not indicate a possible target position. Thus, valid, invalid, and neutral cues provide different target information that can affect where observers align their attention relative to the actual target onset location.

The effects of cueing on visual processing can be determined with a technique called cost/benefit analysis. This procedure involves comparing mean valid-cue and invalid-cue response times to the mean neutral-cue response times. In particular, the *benefit* of valid cueing is the mean neutral-cue response time minus the mean valid-

cue response time. This benefit is thought to reflect the advantage of initiating attentional alignment with the target location before the target onset (e.g., Posner, Snyder, & Davidson, 1980). In other words, by the time the target appears, an attention shift may have already begun towards the target location following a valid cue, providing a “head start” relative to the neutral-cue condition in which attention is ready to be shifted but no shift destination has been signalled. On the other hand, the *cost* of invalid cueing is the mean invalid-cue response time minus the mean neutral-cue response time. This cost is thought to reflect the delay caused by initiating an attention shift to the wrong location, which must be followed by a realignment of attention to the actual target position (e.g., Posner et al., 1980). Thus, the cost/benefit paradigm is said to allow researchers to record and quantify an observer’s covert-orienting activity.

Cost/benefit analysis involves examining cue effectiveness. *Cue effects* are the difference between mean invalid and mean valid response times and they represent the effect of location cueing on target detection or target identification response times. This measure produces the same result as adding costs and benefits in a cost/benefit analysis paradigm. Note, however, that cue-effect analysis is used in cueing experiments in which an unbiased neutral-cue measure that provides temporal warning information but no location information cannot be obtained (Jonides & Mack, 1984; Wright, Richard & McDonald, in press). Cue-effect analysis is less informative than cost/benefit analysis because it does not indicate whether differences between valid and invalid response times are due to facilitative processes (e.g. a

“head-start” or enhanced visual processing) or due to inhibitory processes (e.g. a “head-start” to the wrong location or inhibited visual processing).

Cost/benefit and cue-effect analysis have led to the discovery of several aspects of covert orienting. In particular, there seem to be two different ways to initiate an attention shift. One is a voluntary shift initiated by the observer and the other involves a more reflexive shift initiation in response to the onset of a visual stimulus. Cueing analysis has also contributed to the development of different models for describing how visual attention may contribute to speeded responses at valid-cue locations. Some proposals describe these effects in terms of purely attentive processes while other proposals describe these effects in terms of both sensory and attentive processes.

Goal-Driven and Stimulus-Driven Attention Shifts

A common finding in attention research is that attention shifts can be initiated in two different ways that involve *goal-driven* or *stimulus-driven* shift initiation procedures. Goal-driven shift initiation procedures are voluntary and appear to depend on top-down processes, while stimulus-driven shift initiation procedures are reflexive under most conditions and appear to depend more on sensory activity generated by a cue onset. Goal-driven shifts are usually prompted by *symbolic cues*, which are “indirect” indicators of the target position. A common example is an arrow that appears at the central fixation-cross location and points to a potential target location (see Figure 1a). In contrast, stimulus-driven shifts are prompted by *direct*

cues, which are visual stimuli such as bar markers that appear abruptly at or near a potential target location (see Figure 1b).

One difference between symbolic-cue cue effects and direct-cue cue effects is the time course of cue effectiveness. The time course reflects changes difference between valid and invalid cues at different times following the appearance of a cue. It is measured by varying the *Cue-Target-Onset-Asynchrony* (CTOA) which is the time interval between the cue onset and the target onset. At short CTOAs, cue effects may be less than optimal in magnitude because cues have had insufficient time to prompt the initiation of all the processes necessary for maximal cue effectiveness. As CTOAs get progressively longer, however, cue effects may increase as more time is available for the processes involved in facilitation to run to completion. Thus, the shortest CTOA that maximizes cue effects may reflect the minimum amount of time required for a cue to produce maximal cue effects at a location. This interval has also been said to reflect the time it takes to shift attention to a cued location (e.g., Cheal & Lyon, 1991a). Symbolic cues and direct cues differ in amount of time needed by each to be maximally effective. More specifically, it appears that direct cues produce optimal cue effects with 100 - 175 ms CTOAs whereas symbolic cues produce optimal cue effects with 300 - 400 ms CTOAs (Cheal & Lyon, 1991a; Müller & Findlay, 1989; Müller & Rabbitt, 1989; Weichselgartner & Sperling, 1987). The time course difference in direct-cue and symbolic-cue cue effectiveness therefore suggests that these cues may initiate attention shifts differently.

One of the reasons why symbolic cues and direct cues have different time courses may be that they do not provide the same type of location information. More specifically, because a symbolic cue usually occurs at the central fixation-cross location, the potential target position must be generated by the observer in a cognitive manner. On the other hand, a direct cue usually occurs at a peripheral location in the visual field. Thus, the potential target position is evident on the basis of the cue's location and does not have to be computed in the same goal-driven manner. This could reduce the amount of time required for cue effects to materialize. In other words, symbolic-cue cue effects may occur more slowly than direct-cue cue effects because the former cues may require more interpretation.

Support for the idea that direct cues require less interpretation than symbolic cues comes from the results of a study conducted to examine the effects of cue eccentricity on target-identification accuracy (Cheal & Lyon, 1991b). In this experiment, an arrow cue appeared either at central fixation, 1° away from fixation, or at a peripheral target location. While the fixation cue acted as a symbolic cue and the peripheral cue acted as a direct cue, the 1° cue may have acted as a symbolic cue that required less interpretation than normal. This is because the direction of the target location was directly indicated by the position of the 1° cue relative to the central fixation cross. Thus, it did not have to be computed based on the cue's form (i.e., where the apex of the arrow cue pointed to). The data indicate that 1° -cue cue effects peaked faster than symbolic-cue cue effects, but peaked slower than direct-cue cue

effects. These results are consistent with the idea that symbolic-cue interpretation delays cue effectiveness relative to the direct-cue case.

Symbolic-cue and direct-cue cue effects also differ in how each is affected by extraneous cognitive activity. In particular, the results of one experiment indicate that secondary distractor tasks, such as recalling letter sets, attenuate symbolic-cue cue effects but have little effect on direct-cue cue effects (Jonides, 1981). Because performing the memory task required cognitive effort, it may have interfered with certain top-down functions that are specific to goal-driven attention shifting. This idea is also supported by data indicating that task difficulty has a greater influence on symbolic-cue cue effectiveness than on direct-cue cue effectiveness (Weichselgartner & Sperling, 1987). Thus, the disruptive effect of distracter cognitive tasks on symbolic-cue cue effects suggests that the processes mediating these types of effects rely more on cognitive functioning than the processes mediating direct-cue cue effects.

Other studies suggest that observers may play a more active role in goal-driven cue effectiveness than in stimulus-driven cue effectiveness. For example, in one experiment, a group of observers was instructed to ignore a cue while another group was instructed to use the cue (Jonides, 1981). With symbolic cues, cue effects occurred in the “use” group but not in the “ignore” group. With direct cues, however, cue effects occurred in both groups. This suggests that goal-driven cue effects require an observer’s active participation. Further evidence supporting this claim comes from experiments that vary cue validity. Cue validity represents the probability that a

target will occur at a cued location. In other words, the higher a cue's validity, the more likely it is to convey correct target-location information which makes it more useful for anticipating the target's potential onset location. Typically, with symbolic cues, costs and benefits only occur if cue validity is high. However, with direct cues, cue effects occur when cue validity is high or low (Jonides, 1981, Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). Similarly, another study showed that high cue validity reduced the time required for symbolic-cue cue effects to occur but had no effect on the time required for direct-cue cue effects to occur (Weichselgartner & Sperling, 1987). Taken together, these results suggest that goal-driven cue effectiveness may involve voluntary and controlled processing while stimulus-driven cue effectiveness may involve processes that are more associated with a direct-cue onset.

Models of Attention

Based on data from location cueing investigations, researchers have developed different models of the processes underlying cue effectiveness. These can be separated into three categories according to the metaphors they use to describe the source of the cue effects. These are spotlight models, zoom lens models, and activity-distribution models.

A typical description of a spotlight model involves a beam of attention that moves around the visual field "illuminating" specific locations by enhancing processing at those locations. The attentional focus is assumed to circumscribe only a single region of visual space. Thus, attending to different locations must involve

mechanisms that move the spotlight from one location to another. One possibility is that the spotlight moves between locations by passing through all intermediate positions in an analogue manner (see Figure 2; Shulman, Remington, & Mclean, 1979). Spotlight models also posit that the beam of attention is indivisible. In particular, the results from several investigations suggest that attention cannot be aligned with multiple discontinuous locations in visual space (Keifer & Siple, 1987; McCormick & Klein, 1990; Posner et al., 1980). In these experiments, observers were presented with symbolic cues indicating a probable target onset at two possible locations, and were instructed to attend to both regions. The results indicate that attention could not be discretely allocated to both locations because positions in between the cued locations experienced response benefits instead of the response costs expected if attention was directed at the cued locations but not between them. Furthermore, benefits were greatest at the intermediate positions suggesting that, when instructed to divide their attention between two locations, observers may instead focus their attention at a single position midway between the cued locations (e.g., Keifer & Siple, 1987; McCormick & Klein, 1990). The notion that the attentional focus is indivisible is also supported by experiments involving either distractor cues or targets that appear while attention is already focused at another location. In these studies, an observer's attention was pulled to a location with a direct cue (Müller & Rabbitt, 1989; Warner et al., 1990) or held at a location with a highly-valid cue (Yantis & Jonides, 1990). The subsequent onset of a second stimulus had no effect until after attention appeared to be disengaged from the first

location. This suggests that once attention is concentrated at one location, alternative locations receive attention, not by diverting a portion of the focus away but by drawing the entire focus completely away from the initial location. In summary, the results from several investigations provide support for the central assumption of attention-spotlight models that the focus of visual attention is indivisible.

Zoom-lens models of attention are similar to spotlight models in that they also assume a unitary attentional focus. However, they differ from the spotlight proposals in that the spatial extent of focused attention is free to vary (Eriksen & Yeh, 1985). This means that the spread of attention around a location can change according to the size of an attended stimulus. For example, in one study, the size of the area surrounding a direct cue in which cue effects were observed was said to vary as a function of the cue size (Henderson, 1991). Another difference between spotlight and zoom-lens models involves how attention is shifted to cued locations. More precisely, spotlight models hold that attention is shifted by moving the beam of attention, whereas zoom-lens models hold that attention is shifted by changing the size of the attentional focus (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). In other words, attention alignment based on a zoom-lens model would begin with a defocusing of attention at the initial location so that the extent of the attended area went from narrow to broad (see Figure 3). The next step would involve refocusing attention at the new location so that the attentional distribution contracted from a broad extent to a narrow extent around the new location. Evidence for this variable-focus account comes from a study that used symbolic cues to direct attention to a

specific location and measured the spatial extent of cue effects over time (Shepard & Müller, 1989). At short CTOAs, cue effects encompassed a large area around the cued location and as the CTOAs got progressively longer the spatial extent of the effected region became smaller. Therefore, while both zoom-lens and spotlight models account for attention shifts, they differ in the ways in which the shifts are carried out.

Along with a common underlying assumption that the attentional focus is indivisible, spotlight and zoom-lens models are also similar in that they describe cue effects purely in terms of attentive operations. In particular, these models posit that the cue effects experienced at cued locations can be attributed entirely to attention-related processing enhancement. In contrast, another type of unitary-focus model posits that, under some conditions, cue effects can be due to attention-related processing and sensory-related processing. Sensory-related cue effectiveness seems to be associated with stimuli, such as direct cues, that appear abruptly in the visual field (Müller & Humphreys, 1991). Support for the involvement of a sensory component comes from psychophysical studies that suggest that direct cues are more likely to affect perceptual sensitivity, while symbolic cues are more likely to affect decision processes (e.g., Müller & Humphreys, 1991). Thus, in contrast to purely attentive spotlight and zoom-lens models, this alternative set of models describes direct-cue cue effects as involving both attentional and sensory components.

One sensory/attentive proposal is the activity-distribution model (Laberge & Brown, 1989). This model holds that cue effects occur in the form of location-

specific activation gradients within a representation of visual space. The activation can be initiated by sensory sources such as cue onsets or by goal-driven sources such as an observer's expectations about a cue's usefulness. Moreover, these gradients facilitate visual processing according to the level of activation at a location and if this level surpasses a certain threshold, a unitary channel of attention opens up at that location. Thus, the activity-distribution model provides an explanation of cue effectiveness that combines both sensory and attentive cue effects and describes two different ways to initiate attentional alignment with a location (stimulus-driven and goal-driven).

The relationship between processing activation and focused attention has implications for how attention is shifted to different locations. More specifically, with the activity-distribution model, attentional alignment involves the accumulation of an activation gradient at a to-be-attended location and the attenuation of an activation gradient at the currently-attended location (see Figure 4). This causes the attention channel to close at its present location and to open up at the new location once the gradient at the latter location reaches a particular threshold. This type of shift procedure incorporates both attentive and preattentive processing operations. The attentive processing can be similar to the attentional processing enhancement described in spotlight and zoom-lens models and occurs once the attention channel is open. The preattentive processing is based on the development of activation gradients and is closely tied to the occurrence of sensory activity in the visual field. More specifically, activation gradients in a representation of the visual field indicate

potential attention-shift destinations, and the activity levels associated with those gradients indicate the likelihood of an attention channel opening at a location (i.e., larger gradients are closer to threshold). In other words, the preattentive aspect of this model enables processing at multiple locations (multiple activity gradients are possible) and provides a measure of the processing priority associated with each location as given by the size of the activity gradients. Thus, the activity-distribution model describes a system that can focus attention at specific locations as well as localize and prioritize multiple unattended locations.

Preattentive Localization

Evidence supporting the involvement of sensory activity in visual processing comes indirectly from studies indicating that some visual stimuli are preattentively localized. Preattentive localization involves registering or encoding the positions of certain stimuli without attending to them. This has been observed in studies of visual search in displays that contain abrupt-onset stimuli (Yantis & Johnson, 1990; Yantis & Jones, 1991). In these experiments, observers searched for a target letter among other distractor letters arranged in a circular array around the central fixation cross (see Figure 5). In each trial, half of the items appeared abruptly in the display, while the other half of the items emerged gradually from a set of camouflage placeholders. In general, observers detected abrupt-onset targets faster than they detected gradual-onset targets and this advantage continued for abrupt-onset targets accompanied by up to three abrupt-onset distractors. When an abrupt-onset target appeared with four or more abrupt-onset distractors, the response-time difference between abrupt-onset and

gradual-onset targets diminished, suggesting that abrupt-onset targets were no longer more likely to be detected before gradual-onset targets. These data were said to reflect the existence of a mechanism that localized and assigned a higher processing priority to approximately four abrupt-onset stimuli. This is consistent with the idea that sensory activity can prompt visual processing outside the attentional focus.

The prioritization mechanism might also function in conjunction with a unitary attentional focus to make scanning a visual scene more efficient. More specifically, the locations of abrupt-onset stimuli may be encoded even if those locations are not attended immediately following their onset. In one experiment, when observers actively focused their attention at a location, a stimulus onset elsewhere in the display did not divert their attention from the first location (Yantis & Jonides, 1990). Once attention was disengaged from the initial location, however, the new stimulus seemed to be processed with a higher priority if it had an abrupt onset rather than a gradual onset. This suggests that the abrupt-onset location information was maintained even though the stimulus did not produce any cue effects when it first appeared. Thus, a preattentive mechanism may be involved in localizing abrupt-onset stimuli that appear outside the attentional focus and in redirecting attention to those stimuli once it has been disengaged.

Further evidence for preattentive localization is that observers seem to have the ability to simultaneously follow up to four or five randomly moving objects (Pylyshyn & Storm, 1988). In these experiments, observers were shown displays containing several '+' signs (see Figure 6). A subset of the '+' signs (targets) was

briefly flashed and observers were instructed to keep track of the target items. After all of the items moved quasi-randomly in the display for several seconds, observers were asked if a particular '+' sign was one of the originally flashed targets. They were highly accurate in determining whether or not the item in question belonged to the flashed subset when they were following up to four or five targets. These results could not be accounted for by a unitary attentional focus that serially scanned each target location as the items moved, which suggests that stimulus tracking may occur preattentively and in parallel (Pylyshyn & Storm, 1988). Thus, preattentive localization not only seems to provide a way to record stimulus-onset activity, but may also be involved in maintaining the position of a stimulus if it moves to new locations.

Investigations of a phenomenon known as inhibition-of-return (IOR) also provide support for the operation of a preattentive localization mechanism in visual processing. IOR occurs in specific experimental situations and is characterized by delayed detection response times for targets appearing at previously-cued locations (Maylor, 1985; Posner & Cohen, 1984, Possamai, 1985). Typically, after a direct-cue onset, a target appearing at the cued location is detected faster than a target appearing at an uncued location. If the direct cue is followed by a second direct cue at another location, however, a target appearing at the first-cue location will be detected *slower* than a target appearing at an uncued location. This is thought to reflect a suppression of processing at the first-cue location (Posner & Cohen, 1984). One account of how inhibition occurs is that direct-cue positions are localized and briefly processed to

determine their relevance to the current visual task; if these locations are deemed unimportant then they are inhibited (Wright, Richard, & McDonald, 1994). Thus, IOR may play a role in biasing visual processing away from some previously analyzed stimuli so that they are not processed again.

The results of some studies suggest that preattentive localization may be involved in IOR. In particular, the data from several experiments indicate that IOR can occur simultaneously on opposite sides of the central fixation cross (Posner & Cohen, 1984; Wright & Richard, 1993) and in at least four spatially separate locations (Wright & Richard, 1994). These findings imply that IOR may not be mediated by purely attentive processes because an indivisible attentional focus would not be able to inhibit more than one location at a time. Along with the capability to inhibit several stimuli, the mechanisms underlying IOR also seem to bind response inhibition dynamically to a stimulus instead of to its location. For example, in one experiment, IOR was produced at the onset location of a peripheral direct cue when this cue was followed by second direct cue at the central fixation-cross location (Tipper, Driver, & Weaver, 1992). If the first cue moved to a new location before the target appeared, however, inhibition occurred not at the cue's original position but at the cue's new position, suggesting that IOR moved with the cue to the new location (see Figure 7). Taken together, these results imply that IOR may be mediated by a nonattentional mechanism that can keep track of multiple stimuli, even if their positions change.

The previous cases indicate that certain visual stimuli are processed to some degree even when they are not actively attended to. In particular, functions such as

prioritizing, tracking, and inhibiting stimulus locations seem to occur simultaneously at multiple positions in visual space. On the face of it, some researchers may feel that this contradicts other findings suggesting that attentive processing is characterized by an indivisible unitary focus. An alternative explanation is that operations like prioritizing, tracking, and inhibiting may operate at a preattentive level, independent of focused attention. One reason why these processes may function without attention is that they may instead be driven by sensory activity. This is supported by the fact that each of the described preattentive processes operated on stimuli that either flashed or appeared abruptly in the visual field. Thus, visual processing mediating facilitation in location cueing displays may consist not only of an attentive stage, but also of a stimulus-driven preattentive stage.

EXPERIMENT 1

Experiment 1 was designed to determine whether or not sensory processes, such as those described by the activity-distribution model, contribute to cue effects. If sensory activity is involved, then it may be possible to produce cue effects independent of focused attention. One way to test for attention-independent cue effects due to location cueing appears to be to simultaneously present multiple direct cues at different locations. This is because attention-related cue effects seems to occur only in a single continuous region of visual space (e.g., McCormick & Klein, 1989). If cue effects are recorded at more than one of the cued locations, it would suggest that stimulus onsets outside the unitary region of attentional focus could produce cue effects. This idea is supported by the results of previous studies

indicating that stimulus-driven cue effects can occur with equal magnitude when cues are presented at either a single location or at two spatially discontinuous locations at the same time (Wright, 1994; Wright et al., in press). Thus, the multiple-direct-cue paradigm was used in Experiment 1 to test for cue effects that are independent of focused attention.

The results from the first experiment were expected to be consistent with the predictions of either a purely attentive or a sensory/attentive account of cue effectiveness. Purely attentive proposals hold that cue effects are entirely the result of focused visual attention and include spot-light and zoom-lens models. In contrast, a sensory/attentive proposal holds that cue effects can be the product of both focused attention and preattentive sensory activity. These accounts generate different predictions under the same multiple-cue conditions. With a purely attentive approach, cue effects should only occur at one location on a given trial regardless of the number of cues presented because the region of focused attention is thought to be indivisible. Therefore, over trials, the average cue-effect magnitudes should vary as a function of the number of cues presented. For example, on single-cue valid trials, the target should appear at the attended location on 100% of the trials, yielding an optimal average cue-effect value. With two cues, however, the target should only appear at the attended cued location on 50% of the valid trials because only one location can be attended to at a time. In other words, the cue-effect magnitude in the two-cue condition should be half as much as the cue-effect magnitude in the single-cue condition because average response times would consist of 50% trials with cue

effects and of 50% trials without cue effects. Continuing with this logic, three and four cues should produce average cue-effect magnitudes of 33% and 25% of the maximal amount. Thus, the purely attentive model clearly predicts an inverse relationship between average cue-effect magnitudes over trials and the number of simultaneously cued locations.

The purely attentive account of cue effectiveness following multiple cues is based on an assumption that only a single cued location can be attended to at a given time. Following this logic, other researchers claim that, with multiple cue presentation, the spatial extent of focused attention may change to accommodate more than one cued location (McCormick, 1995). For example, with one cue, attention might be focused exclusively at the cued location. With two or more cues, however, the focus might expand so that multiple cued locations, and all the intermediate regions, would be encompassed by attention (see Figure 8). Assuming that cue-effect levels do not vary in relation to the size of the focus¹, this account predicts a different pattern of cue effects in the multiple-cue conditions than in the single-cue condition. More precisely, some invalid-cue response times following multiple-cue presentation would be faster than those following single-cue presentation because the target would appear in the attended region between multiple cued locations on some proportion of these trials. Thus, mean response times in this case would be composed of trials when the target appeared outside the attentional focus (no cue effects) and composed of trials when the target appeared inside the attentional focus (cue effects present). This prediction can be directly tested by examining invalid trials in which a target

appears at a location in between two cues. If a single attentional focus encompassed multiple cues, then mean invalid response times for “between” trials should be comparable to mean valid-cue response times. The variable-spatial-extent of attention proposal therefore holds that invalid response times on multiple-cue trials should be faster than on single-cue trials and that cue effects should not be confined exclusively to cued locations.

A model that incorporates sensory processes in cue effects makes a different prediction. More precisely, cue effects may occur at unattended direct-cue locations because some cue effects may be associated with sensory activity triggered by a stimulus onset. In this case, as long as the target appeared at a cued location, responses to that target should be faster than responses to a target presented at an uncued position. Cue-effect magnitudes would not change in relation to the number of cues presented because cue effects would occur at all cued locations. In addition, sensory-related cue effectiveness should be confined to cued locations. That is, when a target is presented between two invalid cues, mean response times should still be slower than mean valid response times (unlike the variable-spatial-extent proposal). Thus, a sensory/attentive account of cue effectiveness predicts both constant cue-effect magnitudes for different numbers of cues and cue effects that only occur at cued locations.

Method

Subjects. Twelve Simon Fraser University students were given course credit for participating in the experiment. All subjects had normal or corrected-to-normal vision.

Apparatus. A 286-based IBM compatible computer controlled the experiment timing and stimulus presentation. Stimuli were displayed on a 14-inch colour monitor. Response times were recorded with a button box interfaced with the computer. Observers were tested in a dimly lit room in order to minimize reflections and an adjustable chin rest was used to maintain head position at a distance of approximately 60 cm.

Stimuli. All stimuli were presented on a black (unlit) background. A light grey fixation cross ($0.4 \times 0.4^\circ$) remained visible in the centre of the display throughout the experiment. Cues were light grey bars ($0.8 \times 0.2^\circ$) and the target was a bright-white line ($1.1 \times 0.1^\circ$) tilted either to the left (half of the trials) or to the right (half of the trials) at a 45° angle.² There were eight possible cue and target positions arranged in a circular array around the fixation cross (see Figure 9a). All locations were 6.2° from the fixation cross and 5.5° from adjacent locations. Cues were presented just below potential target locations so that cues and targets did not overlap when both occurred at the same location.

Procedure. Subjects were instructed to keep their eyes on the fixation cross at all times and to press the response button as quickly as possible after the target onset. Each trial began with a 1000 ms inter-trial interval (ITI). Then, one to four cues were

simultaneously presented at randomly-selected locations (see Figure 9b). Following a second delay (CTOA), the target appeared at one of the possible target locations and remained visible until the subject pressed the response button. Response times were measured based on the interval between the target onset and the button press. All cues and target were extinguished following the observer's response which marked the end of the trial. The target occurred at a location already occupied by a cue on half of the trials and occurred at an empty location on the other half of the trials. The CTOA on data trials was 100 ms. This is short enough to preclude the possibility of eye movements to cued locations (Fischer & Weber, 1993), yet long enough to produce cue effects at the cued locations (Cheal & Lyon, 1991a; Müller & Findlay, 1988; Shepard & Müller, 1989).

The experiment was run in a single one-hour session and each subject was given 30 practice trials before starting the experiment. The session was divided into 20 blocks consisting of 48 data trials randomly interspersed with 16 catch trials which had 1500 ms CTOAs. Catch-trial responses were collected but not analysed because their sole purpose was to minimize response anticipation errors. A brief rest period followed each block.

Design. The experiment consisted of two levels of *Cue-Type* completely crossed with four levels of *Number-Of-Cues*. Cue-type was *Valid* if the target occurred at a cued location and *Invalid* if the target occurred at an uncued location.³ The levels of *Number-Of-Cues* were one, two, three and four simultaneously presented cues on a trial. Each *Cue-Type* and *Number-Of-Cues* combination

occurred with a left tilted and a right tilted target three times in a block and trial type presentation was randomized. In total, there were 960 data trials consisting of 120 trials of each combination and 320 catch trials consisting of 40 trials of each combination.

Results

Response times less than 100 ms and greater than 1000 ms were excluded from the analysis as outliers. Following this, response times less than or greater than three standard deviations from the corresponding condition means were also removed. The average error rate per subject was 4.7%.

A 2x4 repeated measures ANOVA was run on mean response times for each subject in each condition. Within-subjects factors were Cue-Validity (Valid or Invalid) and Number-Of-Cues (1, 2, 3, or 4). Figure 10 shows the mean response times averaged over all subjects. The p -values for all results reported are based on Huynh-Feldt adjusted degrees of freedom to compensate for any violations of the sphericity assumption (see Huynh & Feldt, 1976). The main effect of Cue-Validity was highly significant, $F_{(1, 11)} = 61.102$, $MS_E = 199.215$, $p < 0.001$. This difference is due to consistently faster response times in the Valid condition. In addition, the main effect of Number-Of-Cues was also significant, $F_{(3, 33)} = 5.627$, $MS_E = 77.940$, $p = 0.003$. Slower Invalid reaction times in the one-cue condition account for this difference. And finally, the Cue-Validity by Number-Of-Cues interaction was also significant, $F_{(3, 33)} = 5.694$, $MS_E = 61.950$, $p = 0.003$. This again is due to relatively slow Invalid-cue response times in the one-cue condition. A one-way repeated

measures ANOVA was run on mean error rates for each condition to test for a speed-accuracy trade off. None of the error rates differed significantly, $F_{(7, 77)} = 1.53$, $MS_E = .81$, $p = 0.22$, indicating that a speed-accuracy trade off did not occur.

Cue-effect magnitudes are plotted in Figure 11. Note that the cue effects drop approximately 50% between the one-cue and two-cue conditions but remains roughly constant for the two-cue, three-cue, and four-cue conditions. T-test comparisons revealed that Valid and Invalid response times for each of the Number-Of-Cues conditions differed significantly (see Table 1). Furthermore, comparisons between the single-cue valid condition and the other multiple-cue valid condition were all significant at the $p = 0.002$ level (see Table 2). This indicates that cue effects were greater with one cue than with multiple cues.

I also divided invalid-cue response times for each level of Number-Of-Cues into three conditions based on cue/target proximity to examine the spatial extent of cue effectiveness. The *Invalid₀* group contained trials on which the target appeared with empty positions on either side. The *Invalid₁* group contained trials on which the target appeared with one empty and one cued position on each side. And the *Invalid₂* group contained trials on which the target appeared between two cued positions. *Valid* trials were the same as in the initial analysis and contained all trials in which the target appeared at a cued location. Mean response times and standard deviations are presented in Table 3. Note that these data are excluded for the one-cue and two-cue *Invalid₂* conditions because these cells consisted of very few response times per subject. Inspection of the data suggests that most of the mean invalid-cue responses

had comparable response times across the Number-Of-Cues and were slower than mean Valid-cue responses (see Table 4).

Discussion

The single-location purely attentive account of cue effectiveness following multiple direct cues predicts cue-effect magnitudes that are inversely related to the number of cues presented. In the present data this pattern is observed going from the one-cue to the two-cue conditions but is absent in the remaining conditions. Thus, the equivalence of cue effects in the multiple-cue conditions is inconsistent with the notion that only a single location experienced cue effects. That is, equivalent cue effects could only be accounted for by this model if observers were able to anticipate the correct target onset location just as often even though the number of cued locations varied in each condition. This is an unlikely possibility given the random assignment of cue and target positions. Therefore, the present data are difficult to account for with a model based on cue effects at only a single cued location.

A second account of the data involving a unitary attentional focus is that its spatial extent changed to accommodate more than one cued location. This predicts that cue-effect magnitudes would differ in the multiple-cue and single-cue conditions. However, mean response times for trials in which the target appeared between two cues or adjacent to a single cue do not appear to be faster than mean response times for trials in which the target appeared with at least one empty position on either side. Furthermore, 'in between' and 'adjacent' invalid response times are much slower than the corresponding valid trials, suggesting that intermediate uncued positions were not

equally effected. Thus, based on this analysis, it seems that the variable spatial extent of attentional focus account can be rejected in this case as an explanation of cue effects at multiple locations.

The sensory/attentive proposal posits that cue-effect levels should remain constant as the number of cues increases. The present data are consistent with this pattern in the two-cue to four-cue conditions but not in the change from the one-cue to two-cue conditions. It is therefore tempting to suggest that the sensory/attentive account is inadequate for explaining the observed results. Note, however, that the constant cue-effect magnitudes in the multiple-cue conditions still indicate that cue effects were independent of the number of cues and that they may have occurred simultaneously at each cued location. This is consistent with the idea that direct-cue effects may be mediated by mechanisms capable of modulating visual processing at multiple locations independent of a unitary attentional focus.

On this basis, the sensory/attentive proposal can be modified to provide a better account of Experiment 1 data. In particular, the higher level of cue effects in the single-cue case may have occurred because observers voluntarily attended to the cued location in this condition but not in the multiple-cue conditions. In this situation, the increased cue effects may have been due to the combined effects of sensory and attentive facilitation. Two differences in the single-cue and multiple-cue conditions may have encouraged the greater involvement of focused attention in the former. The target appeared at the cued location on 50% of the trials in the single-cue condition but only appeared at any particular cued location on 12.5-25% of the trials in the

multiple-cue conditions. Thus, observers had more incentive to attend the cued location in the former condition. Furthermore, given that observers only seem able to attend to a single region of visual space, it may have only been possible or useful for them to attend to a cued position in the single-cue condition. Therefore, the possible involvement of focused attention in the single-cue but not the multiple-cue conditions may have contributed to the higher level of cue effectiveness in the former condition.

Another aspect of the present data is that the larger single-cue cue effect was due to slower invalid responses. This seems counterintuitive given that focused attention was used to explain the larger cue effects in the single-cue condition. More specifically, if attention was invoked in addition to sensory processes, one might expect that valid responses would have been speeded because visual processing would have been enhanced. Another possibility, however, is that because attention was focused at the cued location, the detection of the target onset at another location may have been disrupted. For example, the target may have appeared less salient, or observers may have had to disengage their attention from the cued location before processing the target (Yantis & Jonides, 1990). These circumstances would have produced slower invalid response times. Note that conclusions about how processing was affected in the single-cue conditions based on mean response-time comparisons are limited because no neutral condition was included in the experiment. This makes it difficult to determine whether the cueing effect was due to increased “costs” or to increased “benefits” (see Wright et al., in press, for a discussion of the use of neutral trials in cost/benefit analysis). Increased benefits would be associated with enhanced

target processing on valid trials and increased costs would be associated with disrupted target processing on invalid trials. Therefore, while the response times are consistent with the idea that target detection was disrupted in the single-cue condition, claims can only be made on a tentative basis until the source of the cueing difference can be determined.

The results of Experiment 1 raise the possibility that direct cues might generate sensory cue effects under some conditions and attentive cue effects under other conditions. More specifically, with multiple cues, non-attentive cue effects may have occurred simultaneously at multiple locations. On the other hand, with a single cue, goal-driven factors such as higher cue validity and the fact that there was only one possible shift destination may have prompted observers to actively attend to that location. Thus, in the first experiment, the type of cue effects observed at a direct-cue location may have been influenced by different experiment parameters in each Number-Of-Cues condition.

EXPERIMENT 2A

The purpose of Experiment 2a was to determine if both sensory-related and attention-related cue effects could occur in the same multiple-direct-cue display. The reasoning behind this study was that sensory cue effects could be triggered by direct-cue onsets, while attentive cue effects could be generated by giving observers goal-driven incentives to attend to one of the cued locations. This incentive could be provided by singling out one of the direct cues and presenting the target at that location with a high frequency. For example, if a High-Validity red cue appeared

with multiple Low-Validity grey cues, the most efficient response strategy would be to attend to the red-cue location because this is where the target will appear most often. Consequently, cue-effect magnitudes at the High-Validity and Low-Validity locations should differ because the High-Validity location might experience attentive and sensory cue effects while the Low-Validity locations would only experience sensory cue effects. Thus, the existence of two different cue-effect magnitudes for High-Validity and Low-Validity direct cues presented in the same display would provide further support for the idea that cue effects may be composed of different sensory and attentive components.

Method

Subjects. Thirteen Simon Fraser University students were given course credit for participating in the experiment. All observers had normal or corrected-to-normal vision.

Apparatus and Stimuli. All apparatus and stimuli were identical to Experiment 1 except that the High-Validity cue was red and the Low-Validity cues were grey.

Procedure. The procedure was similar to that of Experiment 1. Subjects were instructed to keep their eyes on the fixation cross at all times and to press the response button as quickly as possible after the target onset. Furthermore, they were informed that the target would appear at the red-cue location on 66.7% of the trials. Each trial began with a 1000 ms ITI. After this interval, one red and three grey cues simultaneously appeared at randomly-selected cue locations. Following a second

delay (CTOA), the target appeared at one of the possible target locations and remained visible until the observer pressed the response button (see Figure 12). Response times were measured as the interval between the target onset and the button press. All the cues and the target were extinguished following the observer's response which marked the end of the trial. The target occurred at the red-cue location on 66.7% of the trials, at one of the grey-cued locations on 16.7% of the trials, and at an uncued location on 16.7% of the trials. The CTOA on data trials was 100 ms.

The experiment was run in a single one-hour session and each observer was given 30 practice trials before starting the experiment. The session was divided into 18 blocks consisting of 36 data trials randomly interspersed with 12 catch trials that had 1500 ms CTOAs. Catch-trial responses were collected but not analysed. A brief rest period followed each block.

Design. The *Cue-type* variable consisted of three different cue-target combinations; a target onset at the *High-Validity* cue location, a target onset at a *Low-Validity* cue location, and a target onset at an *Uncued* or empty location. Targets were left tilted and right tilted an equal number of times in each condition. Trial type presentation was randomized. In total, there were 864 data trials consisting of 432 High-Validity, 108 Low-Validity, 108 invalid trials, and 216 catch trials with the same 4:1:1 trial ratio.

Results and Discussion

Response-time outliers were removed using the same procedure as in Experiment 1. The average error rate per subject was 1.8%. A one-way repeated measures ANOVA was run on mean the response times for each subject in each condition. Figure 13 shows mean response times for all subjects. The p -values for all results reported are based on Huynh-Feldt adjusted degrees of freedom to compensate for any violations of the sphericity assumption (see Huynh & Feldt, 1976). The main effect of Cue-type was highly significant, $F_{(2, 24)} = 120.675$, $MS_E = 37.543$, $p < 0.001$. Planned comparisons indicate that this effect was due to a faster mean response time in the High-Validity condition relative to the Low-Validity condition, $t_{(12)} = -5.711$, $p < 0.001$, and relative to the Uncued condition, $t_{(12)} = -13.048$, $p < 0.001$. The mean Low-Validity response time was also faster than the mean Uncued response time, $t_{(12)} = -9.891$, $p < 0.001$. A one-way repeated measures ANOVA was run on mean error rates for each condition to test for a speed-accuracy trade off. None of the error rates differed significantly, $F_{(2, 24)} = 0.36$, $MS_E = 0.86$, $p = 0.69$, indicating that a speed-accuracy trade off did not occur.

The results show that cue effects occurred in both the High-Validity and the Low-Validity conditions, but that cue effects were greater in the former case. These data are consistent with the idea that both attentive and sensory sources can contribute to cue effects. They also support the notion that differences in cue-effect magnitudes between the single-cue and multiple-cue conditions in Experiment 1 may have been due to observers focusing their attention at the cued location when only a single cue

appeared in the display. In particular, comparable cue-effect levels were observed in the High-Validity and single-cue conditions (34 ms vs. 35 ms) and in the Low-Validity and multiple-cue conditions (23 ms vs. 19 ms) of the two experiments. Thus, while abrupt direct-cue onsets seem to produce sensory-related cue effects, goal-driven factors such as high cue validity may also initiate additional attentive processing at the appropriate cued location.

The present data contradict those of a previous study in which goal-driven and stimulus-driven cue effectiveness did not seem to occur simultaneously in the same display (Yantis & Jonides, 1990). That experiment used a highly valid (75-100%) symbolic cue to prompt observers to focus their attention at a location. The cue was followed by an abrupt-onset target or a gradual-onset target at either a cued or uncued position. This procedure produced strong goal-driven cue effects but not the abrupt-onset response advantage usually observed without the cueing manipulation, suggesting that stimulus-driven cue effectiveness does not occur if attention is actively engaged elsewhere in the display. One possible explanation for the difference between my results and theirs is that, in their experiment, the target appeared after attention may have already been engaged because there was a 200 ms time interval between the symbolic-cue onset and the abrupt stimulus onset. In contrast, the High-Validity and Low-Validity cues appeared at the same time in Experiment 2a, ensuring that attention would still be disengaged during Low-Validity cue onset. Thus, the differences may be accounted for if attentional engagement is also considered.

EXPERIMENT 2B

Even though the previous results suggest that focused attention may have caused larger cue effects in the High-Validity condition, differences between the salience of direct cues in the High-Validity and Low-Validity conditions cannot be ruled out as the source of the response-time difference. One such difference was that the High-Validity cue was red while the other cues were grey. Therefore, to eliminate the possibility that the colour difference may have caused the difference in response times, Experiment 2a was repeated with the High-Validity and the Low-Validity cue colours reversed.

Method

Thirteen Simon Fraser University students were given course credit for participating in the experiment. All observers had normal or corrected-to-normal vision. All apparatus and stimuli were identical to Experiment 2a except that the High-Validity cue was red and the Low-Validity cues were grey. The experiment procedure and design were identical to Experiment 2a.

Results and Discussion

Response-time outliers were removed using the same procedure as in Experiment 1. The average error rate per subject was 2.2%. A one-way repeated measures ANOVA was run on mean response times for each subject in each condition. Figure 13 shows the mean response times for all subjects. The p -values for all results reported are based on Huynh-Feldt adjusted degrees of freedom to

compensate for any violations of the sphericity assumption (see Hyunh & Feldt, 1976). The main effect of Cue-type was highly significant, $F_{(2, 24)} = 41.924$, $MS_E = 104.370$, $p < 0.001$. Planned comparisons indicate that this effect was due to faster mean response times in the High-Validity condition relative to the Low-Validity condition, $t_{(12)} = -8.063$, $p < 0.001$, and relative to the Uncued condition, $t_{(12)} = -9.877$, $p < 0.001$. Mean Low-Validity response times were also faster than mean Uncued response times, $t_{(12)} = -3.390$, $p = 0.005$. A one-way repeated measures ANOVA was also run on mean error rates for each condition to test for a speed-accuracy trade off. None of the error rates differed significantly, $F_{(2, 24)} = 0.74$, $MS_E = 0.47$, $p = 0.49$, indicating that a speed-accuracy trade off did not occur. In summary, the same pattern of results as obtained in Experiment 2a occurred with the reversed cue colours. Therefore, this factor can be eliminated as a possible source of the response-time difference between the High-Validity and Low-Validity conditions.

EXPERIMENT 2C

The Experiment 2b data indicate that particular cue colours are not the source of the cue-effect differences between the cue conditions. Another possibility, however, is that the presence of a *unique colour* in the High-Validity condition may have caused the faster responses. More specifically, some studies report that a unique feature may ‘pop-out’ and be processed faster if observers are performing a task defined in terms of the relevant feature (e.g., Folk, Remington & Johnson, 1992; Yantis & Hillstrom, 1994). For example, if observers are instructed to search for a target based on its colour, then the presence of a unique line orientation does not seem

to 'pop-out' but the presence of a unique colour does. Therefore, observers may have responded faster to the High-Validity cue because its colour was unique relative to that of the other cues.

The purpose of Experiment 2c was to determine whether or not the High-Validity cue's unique colour was responsible for the faster responses in that condition. This was done by eliminating observers' incentive to attend to the red cue. Thus, in the present experiment, the target appeared at the red-cue location equally as often as any other cued location. If greater High-Validity facilitation was attention-related in the previous experiments, this additional cue effects should not occur in the present experiment because observers would not be attending to the red-cue location. On the other hand, if the additional cue effectiveness was triggered by the cue's unique colour, a larger cue-effect magnitude should persist in the High-Validity condition.

Method

Thirteen Simon Fraser University students were given course credit for participating in the experiment. All apparatus and stimuli were identical to Experiment 2a. The procedure and design were also identical to those of Experiment 2a except that High-Validity, Low-Validity and Uncued trials occurred with different frequencies. More specifically, the target appeared at the High-Validity location 14% of the time,⁴ at a Low-Validity location 43% of the time (14% at each Low-Validity cued location), and at an Uncued location 43% of the time. Trial type presentation was randomized. In total, there were 756 regular trials consisting of 108 High-

Validity, 324 Low-Validity, and 324 Uncued trials and 252 catch trials with the same 1:3:3 trial ratio. Subjects were told that the target would appear at the red-cue (High-Validity) location with the same frequency as any other cued location.

Results and Discussion

Response-time outliers were removed using the same procedure as in Experiment 1. The average error rate per subject was 1.6%. A one-way repeated measures ANOVA was run on mean response times for each subject in each condition. Figure 13 shows the mean response times for all subjects. The p -values for all results reported are based on Huynh-Feldt adjusted degrees of freedom to compensate for any violations of the sphericity assumption (see Huynh & Feldt, 1976). The main effect of Cue-type was highly significant, $F_{(2, 24)} = 14.057$, $MS_E = 74.491$, $p < 0.001$. Planned comparisons indicate that this effect was due to faster mean response times in the High-Validity condition relative to the Uncued condition, $t_{(12)} = -4.011$, $p = 0.002$, and to faster mean Low-Validity response times relative to mean Uncued response times, $t_{(12)} = -4.139$, $p = 0.001$. Mean High-Validity response times did not differ significantly from mean Low-Validity response times, $t_{(12)} = 1.575$, $p = 0.14$. A one-way repeated measures ANOVA was run on mean error rates for each condition to test for a speed-accuracy trade off. None of the error rates differed significantly, $F_{(2, 24)} = 1.88$, $MS_E = 1.08$, $p = 0.18$, indicating that a speed-accuracy trade off did not occur.

The results show that mean response times for both the High-Validity and the Low-Validity conditions were faster than mean Uncued response times. Moreover,

there was no significant difference between the High-Validity and Low-Validity conditions, indicating that the High-Validity cue's unique colour did not lead to faster responses. The absence of a cue-effect difference also suggests that the incentive to attend to the High-Validity cue may have contributed to the cue-effect differences in the previous two experiments. Thus, the data from the present experiment provide further support for the idea that the High-Validity cue effects in Experiments 2a and 2b were, in part, due to attentive processes.

EXPERIMENT 3

The data from the previous experiments suggest that sensory cue effects produced by direct-cue onsets may occur independent of visual attention. Experiment 3 builds on this idea and was designed as an exploratory investigation of some of the properties of cue effectiveness. The present experiment investigated the time course of multiple direct-cue cue effects. The results of previous direct-cue studies involving a single cued location indicate that cue effects peak at approximately 100 - 175 ms following the cue onset and decreases thereafter (Müller & Findlay, 1989; Müller & Rabbitt, 1989; Weichselgartner & Sperling, 1987). If multiple-cue cue effectiveness is mediated by the same processes, then a similar time course should be observed using multiple direct cues. Experiment 3 employed the same procedure as Experiment 1 except that the CTOA was varied across trials. CTOAs of 100, 200, and 300 ms were used to examine temporal changes in cue-effect magnitudes.

Method

Subjects. Twelve Simon Fraser University students were given course credit for participating in the experiment. All subjects had normal or corrected to normal vision.

Apparatus and Procedure. All apparatus and stimuli were identical to Experiment 1. The procedure was the same as in Experiment 1 except that four cues were presented on all trials and the CTOA for a data trial was either 100, 200, or 300 ms. While the 300 ms condition provided observers with enough time to execute a saccade to a cued location (Fischer & Weber, 1993), I assumed that observers were not moving their eyes to cued locations because eye movements cannot be executed to multiple locations simultaneously. The experiment was divided into 20 blocks consisting of 36 data trials randomly interspersed with 12 catch trials that had 1500 ms CTOAs

Design. The experiment consisted of two levels of *Cue-type* completely crossed with three levels of *CTOA*. *Cue-type* was *valid* if the target occurred at a cued location and *invalid* if the target occurred at an empty location. The levels of *CTOA* were 100, 200, and 300 ms. Each *cue-type* and *CTOA* combination occurred with a left tilted and a right tilted target three times in a block and trial type presentation was randomized. In total, there were 720 data trials consisting of 120 trials of each combination and 240 catch trials consisting of 40 trials of each combination.

Results and Discussion

Response-time outliers were removed using the same procedure as in Experiment 1. The average error rate per subject was 2.7%. A 2x3 repeated measures ANOVA was run on mean response times for each subject in each condition. The within-subjects factors were Cue-Validity (Valid or Invalid) and CTOA (100, 200, & 300 ms). Figure 14 shows the mean response times averaged over all subjects. The p -values for all results reported are based on Huynh-Feldt adjusted degrees of freedom to compensate for any violations of the sphericity assumption (see Huynh & Feldt, 1976). The main effect of Cue-Validity was just significant, $F_{(1, 11)} = 5.133$, $MS_E = 103.949$, $p = 0.045$, and this difference was due to the faster response times in the 100 ms-valid condition. In addition, the main effect of CTOA was also significant, $F_{(2, 22)} = 32.963$, $MS_E = 130.955$, $p < 0.001$. This effect was due to faster response times observed with the longer CTOAs. And finally, the Cue-Validity/Number-Of-Cues interaction also obtained significance, $F_{(3, 33)} = 5.694$, $MS_E = 61.950$, $p = 0.002$, because of a difference between Valid and Invalid response times that was only found in the 100 ms-CTOA condition. Cue-effect magnitudes are plotted in Figure 15. Planned comparisons indicate that Valid and Invalid response times only differed in the 100 ms-CTOA (see Table 5). A one-way repeated measures ANOVA was run on mean error rates for each condition to test for a speed-accuracy trade off. None of the error rates differed, $F_{(5, 55)} = 3.03$, $MS_E = 3.36$, $p = 0.06$, indicating that a speed-accuracy trade off did not occur.

These data indicate that multiple-cue cue effects peak around 100 ms and dissipate within 200 ms. This finding is consistent with other single-cue results that show cue effects peaking around 100 to 175 ms (Müller & Findlay, 1989; Müller & Rabbitt, 1989; Weichselgartner & Sperling, 1987). Thus, the results from Experiment 3 seem to be consistent with the notion that direct-cue cue effects may be mediated by the same mechanisms in single-cue and multiple-cue paradigms.

GENERAL DISCUSSION

The most notable finding of these experiments is that direct-cue onsets may produce cue effects independent of attention. This claim is supported by the occurrence of almost identical cue-effect magnitudes when two, three, or four direct cues appeared at the same time. This is inconsistent with the idea that only a single cued location can be the recipient of cue effects. Otherwise, cue-effect levels should have dropped as an inverse function of the number of cues presented. Moreover, cue effects seemed to be confined to cued locations. This is supported by the observation that mean invalid-cue responses in which the target appeared between two cued locations were comparable to mean invalid-cue responses in which the target appeared between two empty locations. If the spatial extent of the cue-effect region is singular and encompasses multiple cued locations, responses should have been faster in the former condition. Further evidence of attention-independent cue effects is that, in Experiments 2a and 2b, cue effects that were dependent on high cue validity (probably attention related) were observed at the High-Validity-cue location while cue effects independent of this factor were observed at the Low-Validity-cue

locations. In sum, these experiments provide support for the idea that cue effects produced by direct cues can occur independent of visual attention.

The current data are also consistent with other findings indicating that non-attentional processing may occur in response to abrupt stimulus onsets including reports that simultaneous cue effects can occur at two spatially discontinuous locations (Wright, 1994; Wright et al., in press). Other reports of visual processing outside focused attention include prioritizing up to four abrupt-onset stimuli (Yantis & Johnson, 1990; Yantis & Jones, 1991), visually tracking around 4 or 5 flashed stimuli (Pylyshyn & Storm, 1988), inhibiting at least four direct-cue locations (Wright & Richard, 1994), and rapid enumeration (subitizing) of up to four abrupt-onset stimuli (Wright & Richard, 1995). These activities cannot be accounted for by a unitary attentional focus because they all seem to involve simultaneous stimulus localization at multiple positions. Thus, the results in this thesis contribute to a growing body of evidence suggesting that visual processing following location cueing may consist of both attentive and preattentive processing components.

Researchers have proposed different models of preattentive localization and processing. One account involves a mechanism called “Fingers of INSTantiation” or *FINSTs* (Pylyshyn, 1989; Pylyshyn, Burkell, Fisher, Sears, Schmidt, & Trick, 1994). According to this proposal, stimulus tracking is mediated by four or five *FINSTs* that dynamically encode the locations of stimuli. In general, these *FINSTs* “point” to important stimulus representations, linking them with higher-level functions for rapid access and processing. A second account of preattentive processing holds that

temporally decaying *priority tags* are used to record stimulus locations (Yantis & Jones, 1991). In this case, all abrupt-onset stimuli are tagged and thereby designated as items requiring immediate processing. The strength of a tag signal, however, decays rapidly over time so that with multiple simultaneous onsets only a limited subset (usually four or five) of those onsets are processed with priority. Both FINST and priority-tag models are consistent with the present data because they deal with encoding of multiple locations independent of focused attention. The latter proposal is also consistent with the transient nature of multiple-cue cue effects found in Experiment 3.

The present results may have implications for the role that attention is thought to play in direct-cue cue effects. Many researchers claim that stimulus-driven attention shifts are responsible for direct-cue cue effects (e.g., Cheal & Lyon, 1991a; Jonides, 1981; Nakayama & Mackeben, 1989; Posner, 1980). In particular, a direct-cue onset is thought to automatically *pull* attention to the cued location, producing faster detection and more accurate identification of targets appearing at the cued location. The data in this thesis, however, raise the possibility that stimulus-driven facilitation may not always involve visual attention. This claim is based on an assumption that single-direct-cue cue effects in previous experiments are the same as the multiple-direct-cue cue effects in the present experiments. While the present experiments were not designed to directly test this assumption, two findings are consistent with this idea. The first is that multiple cues produce cue effects under conditions of low cue validity, which also occurs in previous research with a single

cue (Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). The second is that both single-cue and multiple-cue procedures produce a similar transient time course of cue effectiveness under low-validity cue conditions (Müller & Findlay, 1989; Müller & Rabbitt, 1989; Weichselgartner & Sperling, 1987). If cue effects are mediated by the same mechanism in both cases, then results suggesting that direct-cue cue effects may occur simultaneously at several locations raise questions about whether or not direct cues automatically pull attention to cued locations (e.g., Jonides, 1980). In other words, the multiple-location cue-effect findings imply that if attention is pulled, it must also be divided among multiple direct-cue locations. Therefore, the present results may make it difficult to retain both the claim that attention is indivisible and the claim that it is always automatically pulled to direct-cue locations.

While the present results provide some information about cue effects may operate following multiple direct cues, several other questions about it are raised. One question is whether or not processes such as FINSTing or priority tagging are involved in stimulus-driven cue effectiveness or if it is entirely a sensory process. This can be tested by replicating Experiment 1 with more than four cues (i.e., 1-8 cues). Initially, with a preattentive-localization account, the observed cue-effect magnitudes should be constant with increasing numbers of cues presented because FINSTing/tagging seems to operate for up to four or five items (e.g., Pylyshyn, 1989; Yantis & Jones, 1991). As the number of cues surpassed the number of positions that can be tagged, however, cue-effect magnitudes should begin to drop as some valid-trial targets would appear at cued locations in which no cue effects occur. In contrast,

cue-effect magnitudes should remain constant regardless of the number of cues with a purely sensory account because as long as the target appeared at a cued location, the corresponding target processing would be speeded. Thus, a modified version of Experiment 1 could provide information about the source of cue effects produced by direct cues.

Another direction for future research involves the effect of attentional engagement on stimulus-driven cue effectiveness. More specifically, the results from Experiment 2a suggest that both stimulus-driven and goal-driven cue effectiveness can occur simultaneously in the same display. Note that previous findings suggest that stimulus-driven cue effectiveness does not occur when attention is already focused at a location (Yantis & Jonides, 1990). As previously described, one explanation for the different results is that the abrupt-onset stimulus appeared 200 ms after the symbolic cue in the earlier study, while the High-Validity and Low-Validity cues appeared simultaneously in Experiment 2a. Thus, observers had time to engage their attention at a location before the abrupt stimulus onset in the former experiment but not in the latter. The effect of attentional engagement can be tested by repeating Experiment 2a with different time intervals between the High-Validity cue onset and the Low-Validity cue onsets (e.g., presenting the High-Validity cue 0, 100, 200, & 300 ms before the Low-Validity-cue onsets). If engaged attention disrupts direct-cue effectiveness, then Low-Validity-cue cue effects should be normal at short intervals and disappear at longer intervals when enough time is available for observers to engage their attention at the High-Validity-cue location. On the other

hand, if stimulus-driven cue effectiveness is unaffected by attentional engagement then cue-effect magnitudes should be the same at all intervals. Thus, the proposed experiment could provide information about the relationship between engaged attention and cue effects produced by multiple direct cues.

The current results suggest that the processes mediating direct-cue cue effects may involve an interaction between sensory and attentive operations because neither purely attentive nor purely-sensory approaches adequately account for the present data on their own.⁵ This interaction is emphasized by results indicating that a low-validity direct cue seems to produce sensory-related cue effects. If an incentive to attend to this cued location is introduced, however, then the same direct cue seems to produce goal-driven cue effects (e.g., the High-Validity cue in experiments 2c and 2a). Thus, the same visual input appears to produce different cue-effect levels dependent on an observer's top-down goals. This raises questions about what level of processing this interaction occurs at. One possibility is that it takes place during what has been called intermediate-level vision (Ullman, 1984). This processing stage is characterized by visual routines such as *indexing* that can be triggered by sensory factors such as stimulus salience or initiated voluntarily by, for example, tracking moving targets. If cue effects are mediated by an intermediate-level stimulus localization routine, then both sensory and attentive processes could activate location-specific cue effects.

In summary, the experiments in this thesis were designed to investigate the effects of multiple direct-cue onsets on target-detection response times. The results

support the notion that cue effects involve an interaction between sensory and attentive processes. This finding has several important implications for how cue effects following direct cues are thought to occur. One is that, under certain conditions, direct cues seem to produce cue effects independent of attention. This provides support for the existence of preattentive localization mechanisms that may mediate interactions between sensory and attentive cue-effect processes. Another implication is that there may be more to stimulus-driven attention shifts than the simple pulling of attention to a cued location. In particular, certain prerequisites, such as high cue validity and only one possible shift destination, may be necessary if a unitary attentional focus is to be pulled to a direct-cue location. Thus, the idea that direct-cue cue effects involve sensory and attentive interactions provides a contrast to more common views, which hold that sensory and attentive systems function independently.

NOTES

1. If the case in which cue effects vary inversely with the size of the focus is used then this account makes essentially the same as predictions as the single location “fixed-extent” account of cue effectiveness.
2. The target was tilted to the left and to the right so that the display would be comparable to other discrimination-task experiments that are not reported in this thesis.
3. Neutral trials were not included because the typical neutral condition with eight cue and target positions involves presenting a cue at every possible location (e.g., Henderson & MacQuistan, 1993; Wright, 1994). In the context of the present experiment, this method would not yield a neutral condition but a multiple-cue condition with eight cues (see Wright et al., in press). Thus, the neutral cue would not solely represent temporal warning effects because cue effects would also occur at neutral-cue locations.
4. Even though the terms High-Validity and Low-Validity do not accurately describe the cue validities in this experiment (they should be reversed), they will be retained to simplify comparisons to Experiment 2a.
5. The larger cue effects in conditions involving high cue validity can also be explained with a model that holds that orthogonal stimulus-driven and goal-driven cue effects combine to produce additive effects instead of interactive effects. However, the idea that separate processes contribute to larger cue effects is less plausible because goal-driven cue effects are not usually observed following 100 ms

CTOAs (e.g., Müller & Findlay, 1989; Müller & Rabbitt, 1989; Weichselgartner & Sperling, 1987). Therefore, an additive model with independent stimulus-driven and goal-driven processes would predict no real differences between high-validity and low-validity cue conditions in the present experiments.

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TABLES

Table 1: *Planned Comparisons for Mean Response Times in Experiment 1*

Comparison	$t_{(11)}$	p
valid vs. invalid (1 cue)	-6.01	0.000
valid vs. invalid (2 cues)	-5.28	0.000
valid vs. invalid (3 cues)	-9.30	0.000
valid vs. invalid (4 cues)	-4.76	0.001

Table 2: *Pairwise Comparisons for Mean Valid Single- and Multiple-cue Response Times in Experiment 1*

Comparison	$t_{(11)}$	p
1 cue vs. 2 cues (valid)	4.86	0.001
1 cue vs. 3 cues (valid)	6.03	0.000
1 cue vs. 4 cues (valid)	-4.00	0.002

Table 3: Mean Valid, Invalid₀, Invalid₁ and Invalid₂ Response Times and Standard Deviations in Experiment 1 (in ms)

Number of Cues	Cue Validity							
	Valid		Invalid ₀		Invalid ₁		Invalid ₂	
	RT	SD	RT	SD	RT	SD	RT	SD
1	366	71	402	81	404	78	-	-
2	366	77	392	84	376	87	-	-
3	364	75	383	74	383	62	384	81
4	366	73	390	85	382	79	385	85

Table 4: Comparisons for Valid trials versus Invalid₀, Invalid₁, and Invalid₂ trials in Experiment 1. Note, the critical Bonferroni corrected p-value with a 10% Family-wise error rate is 0.01.

Number of Cues	Comparison: Valid vs.					
	Invalid ₀		Invalid ₁		Invalid ₂	
	$t_{(11)}$	p	$t_{(11)}$	p	$t_{(11)}$	p
1	-6.40	0.000	-2.77	0.018	-	-
2	-4.23	0.001	-2.68	0.022	-	-
3	-2.059	0.064	-8.356	0.000	-1.27	0.230
4	-2.822	0.017	-3.639	0.004	-2.77	0.018

Table 5: *Planned Comparisons for Mean Response Times in Experiment 3*

Comparison	$t_{(11)}$	p
valid vs. Invalid (100ms)	-5.62	0.000
valid vs. invalid (200ms)	-1.17	0.265
valid vs. Invalid (300ms)	0.58	0.571

FIGURE CAPTIONS

Figure 1: (a) Typical symbolic-cue display. The potential target (box) location is pointed to by the arrow. (b) Typical direct-cue display. The potential target (box) location is indicated by the onset location of the direct-cue (bar).

Figure 2: Visual attention shift to a cued location with a Spotlight model. An observer's visual input and attention-level internal representations are indicated by the horizontal plains. (1) The spotlight of attention (white cylinder) is focused at the central fixation cross location. (2) & (3) A direct-cue onset triggers the spotlight to shift to the cued location. (4) The spotlight of attention is focused at the cued location.

Figure 3: Visual attention shift to a cued location with a Zoom-lens model. An observer's visual input and attention-level internal representations are indicated by the horizontal plains. (1) The beam of attention (white cylinder) is focused at the central fixation cross location. (2) A direct-cue onset causes the beam to expand until (3) it spans a broad region of the visual field (including the cued locations). (4) The beam of attention contracts until it is focused at the cued location.

Figure 4: Visual attention shift to a cued location with an Activity Distribution model. An observer's visual input, along with preattentive-level and attention-level internal representations are indicated by the horizontal plains. (1) An activity gradient (white bell) is present at the central fixation cross location. (2) A direct-cue onset causes the formation of a new gradient at the cued location. (3) The new gradient enlarges, driven by either sensory activity produced by the cue onset or by top-down

goals to attend to the cued location. (4) Once the gradient's size surpasses a certain threshold, a channel of focused attention opens up at the cued location.

Figure 5: Typical visual search display with abrupt-onset stimuli. The search target (P) has an abrupt onset if it appears at an empty location or has a gradual onset if it appears at one of the place-holder locations.

Figure 6: Stimulus-tracking display. Stimuli to be tracked are flashed at the beginning of a trial then all stimuli move quasi-randomly for several seconds. Following this, a target stimulus is flashed and observers must indicate whether or not it was one of the initially flashed stimuli.

Figure 7: Object-based inhibition-of-return display. A direct cue at a peripheral location is followed by a second direct cue at the central fixation-cross location. The peripheral direct cue moves to a new location before the target appears at the peripheral cue's onset location, at the peripheral cue's new location or at an uncued location.

Figure 8: The predicted spatial extent of the attention focus (grey region) in single-cue and multiple-cue conditions. Note that a target can appear at an *uncued* location within the attention focus in the multiple-cue condition but not in the single cue conditions.

Figure 9: (a) All of the possible cue and target positions in Experiment 1. (b) Stimulus display in Experiment 1. One, two, three, or four direct cues (bars) appear simultaneously around the fixation cross. Following a certain time interval (CTOA)

the target appears at direct-cue location (valid trial) or at an uncued location (invalid trial).

Figure 10: Mean valid and invalid response times (ms) over the number of cues presented in Experiment 1.

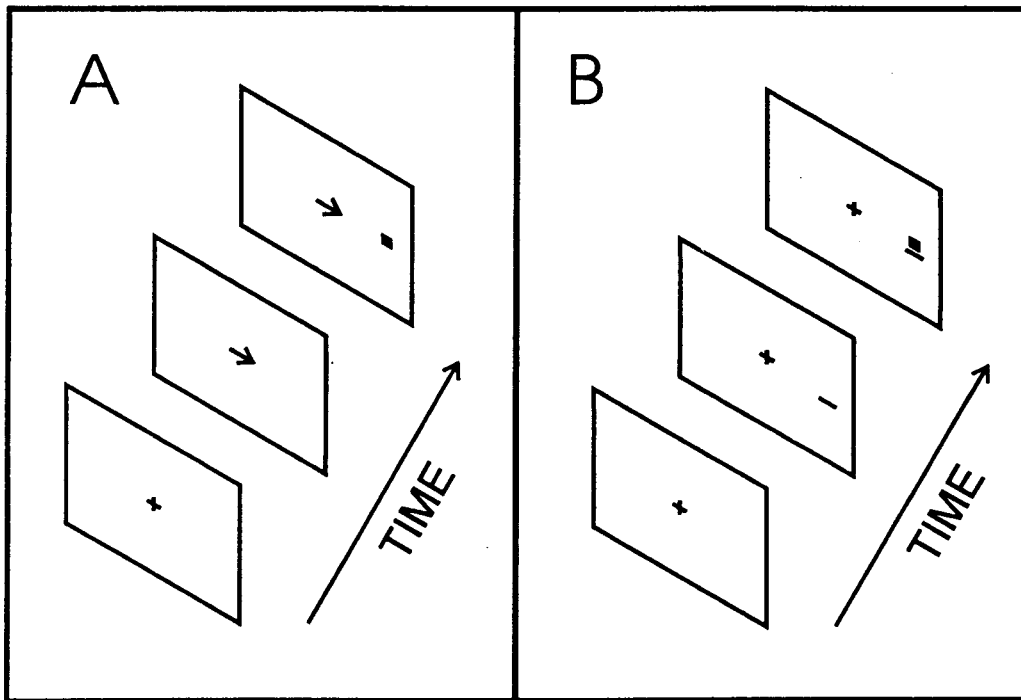
Figure 11: Mean cue-effect magnitudes (ms) over the number of cues presented in Experiment 1.

Figure 12: Stimulus display used in Experiment 2. One red direct cue (empty bar) and three grey direct cues (filled bars) appear simultaneously around the fixation cross. Following a certain time interval (CTOA) the target appears at red-cue location (High-Validity trial), at a grey-cue location (Low-Validity trial) or at an uncued location (uncued trial).

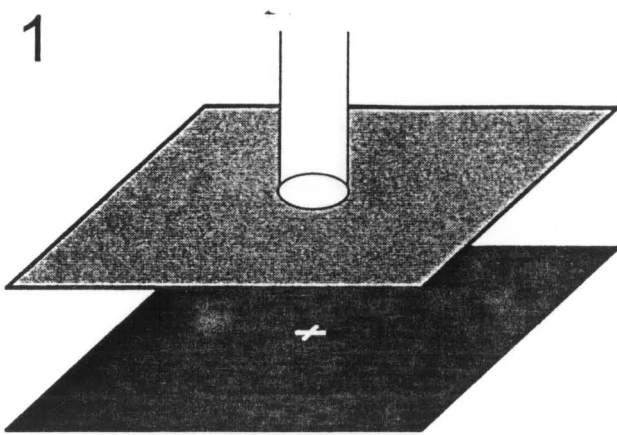
Figure 13: Mean High-Validity, Low-Validity, and Uncued response times (ms) in Experiment 2a, 2b, and 2c.

Figure 14: Mean valid and invalid response times (ms) over CTOA in Experiment 3.

Figure 15: Mean cue-effect magnitudes (ms) over CTOA in Experiment 3.



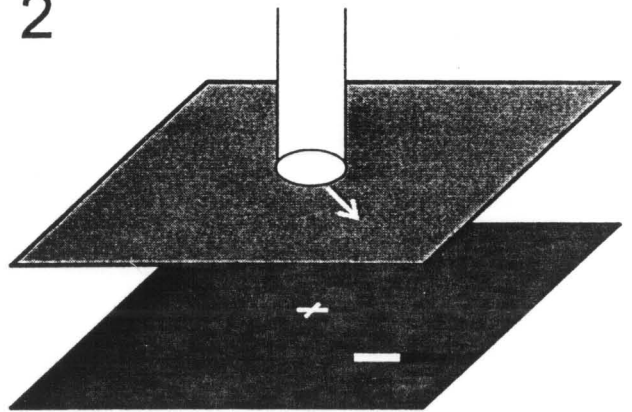
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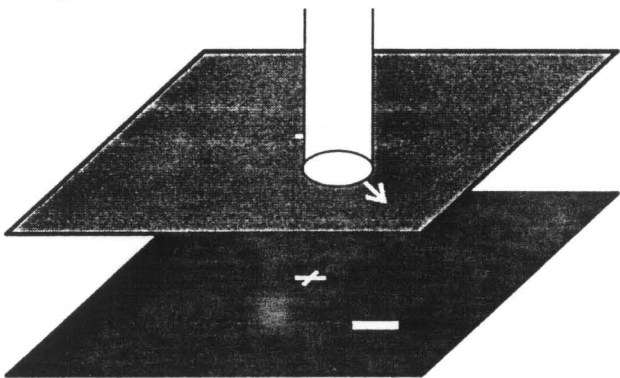
ATTENTIVE LEVEL

VISUAL SCENE

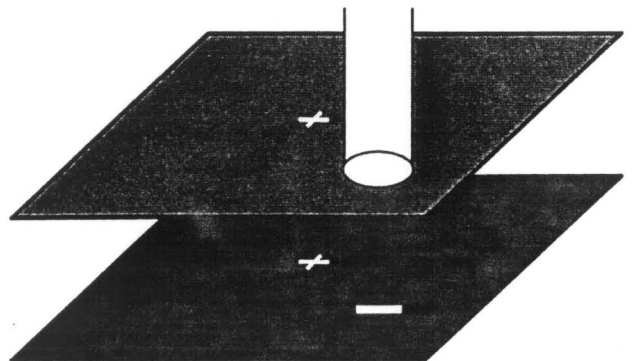
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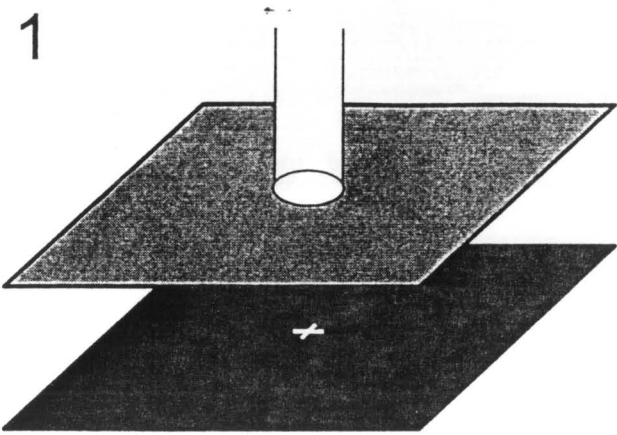
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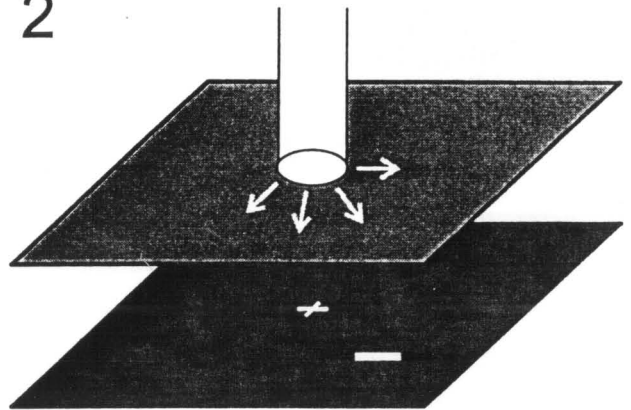
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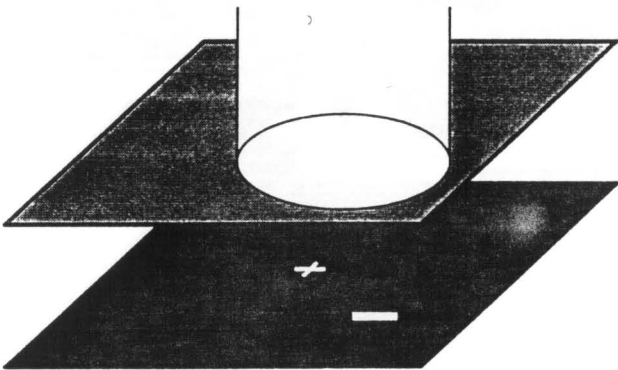
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VISUAL SCENE

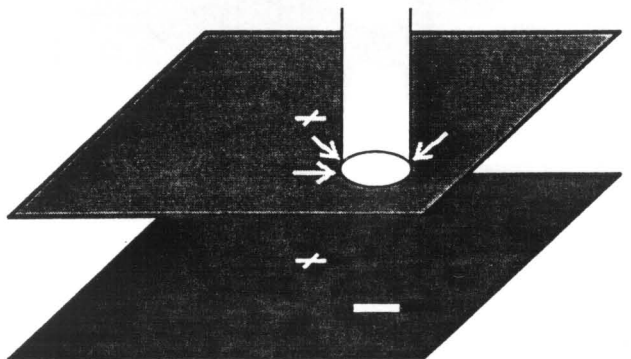
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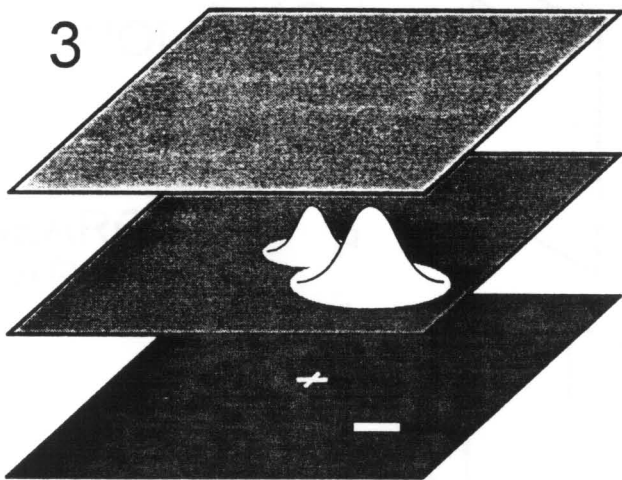
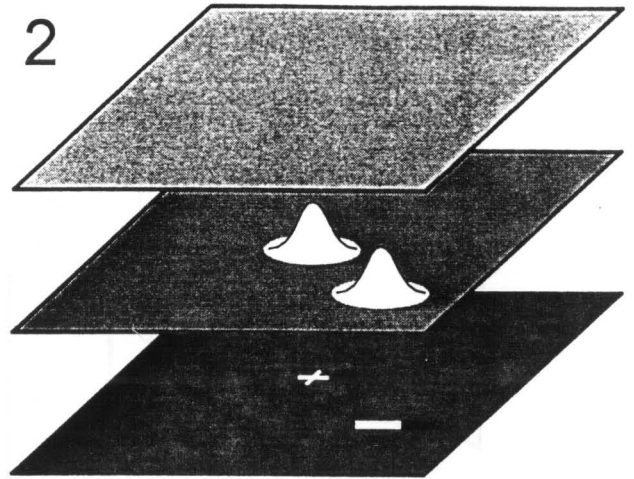
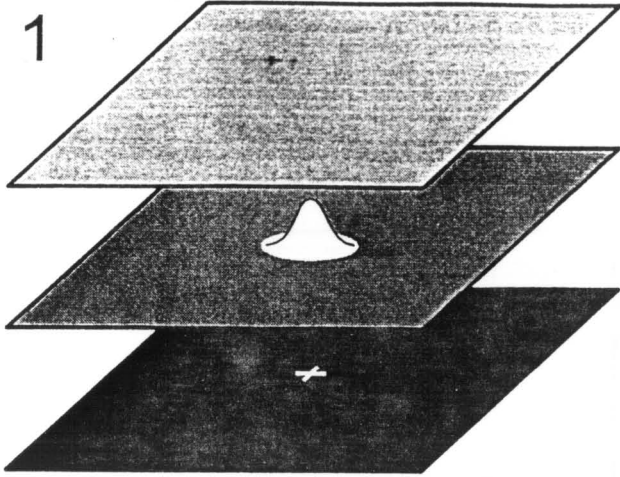
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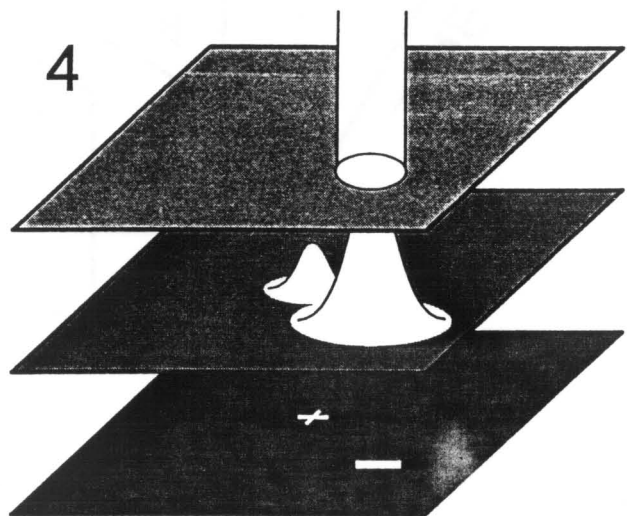
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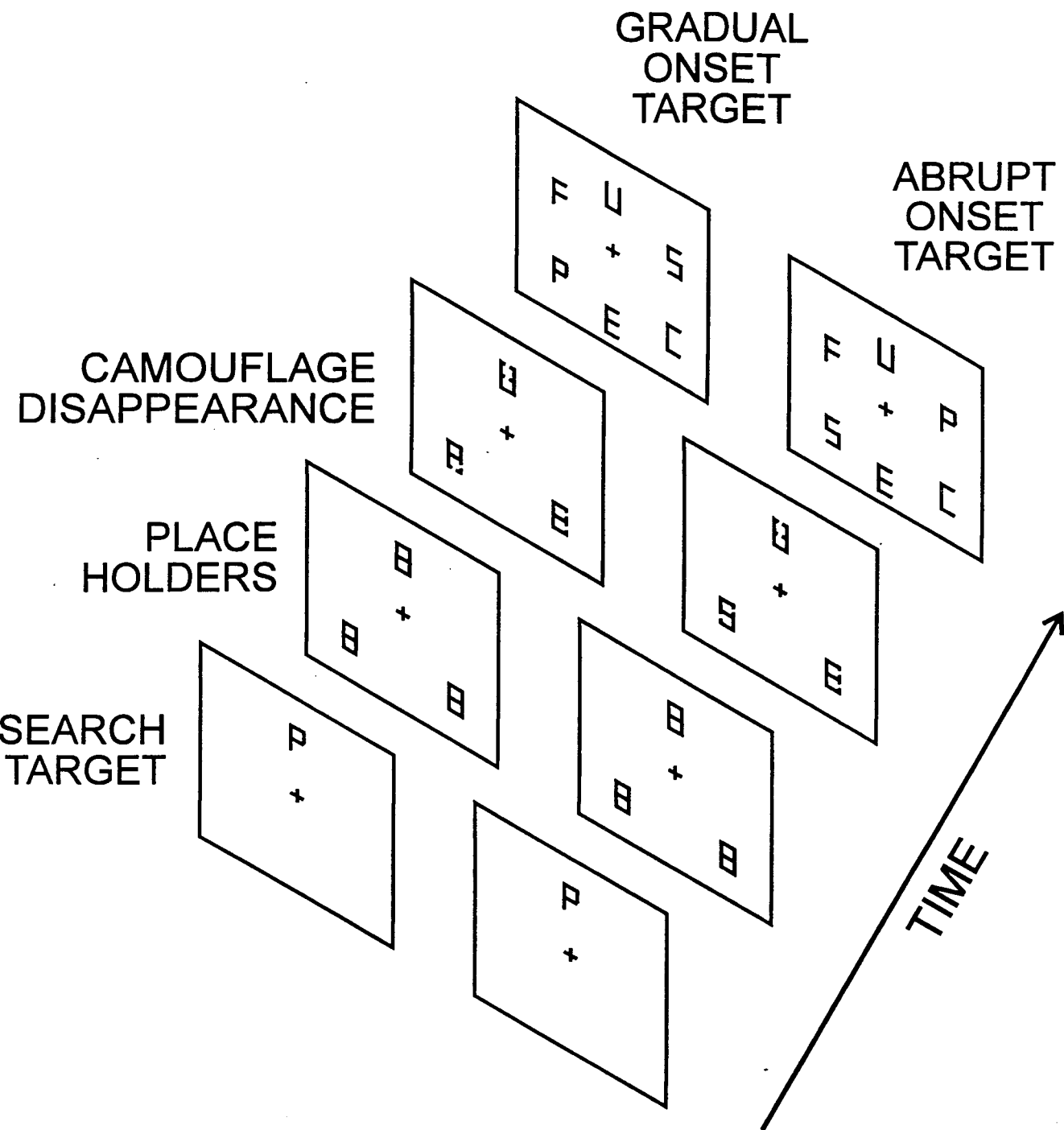
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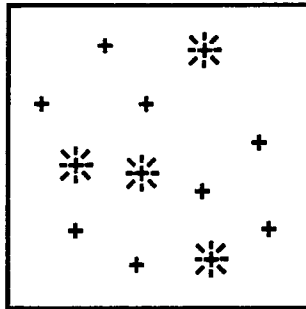
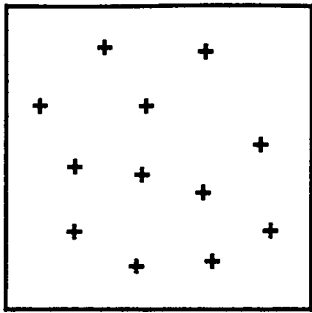
VISUAL SCENE



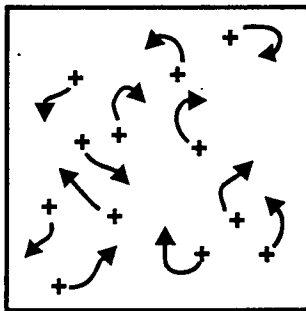
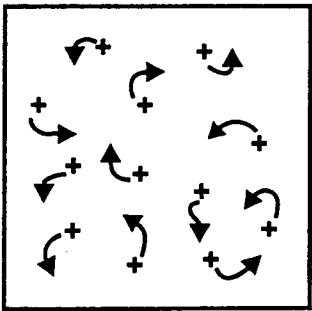
ATTENTION CHANNEL
OPEN



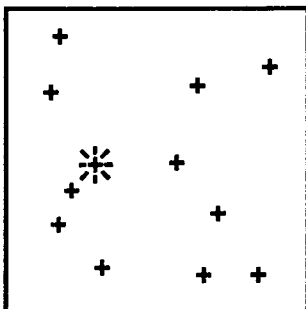
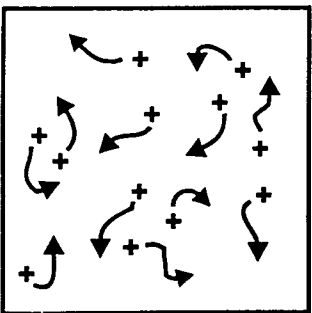




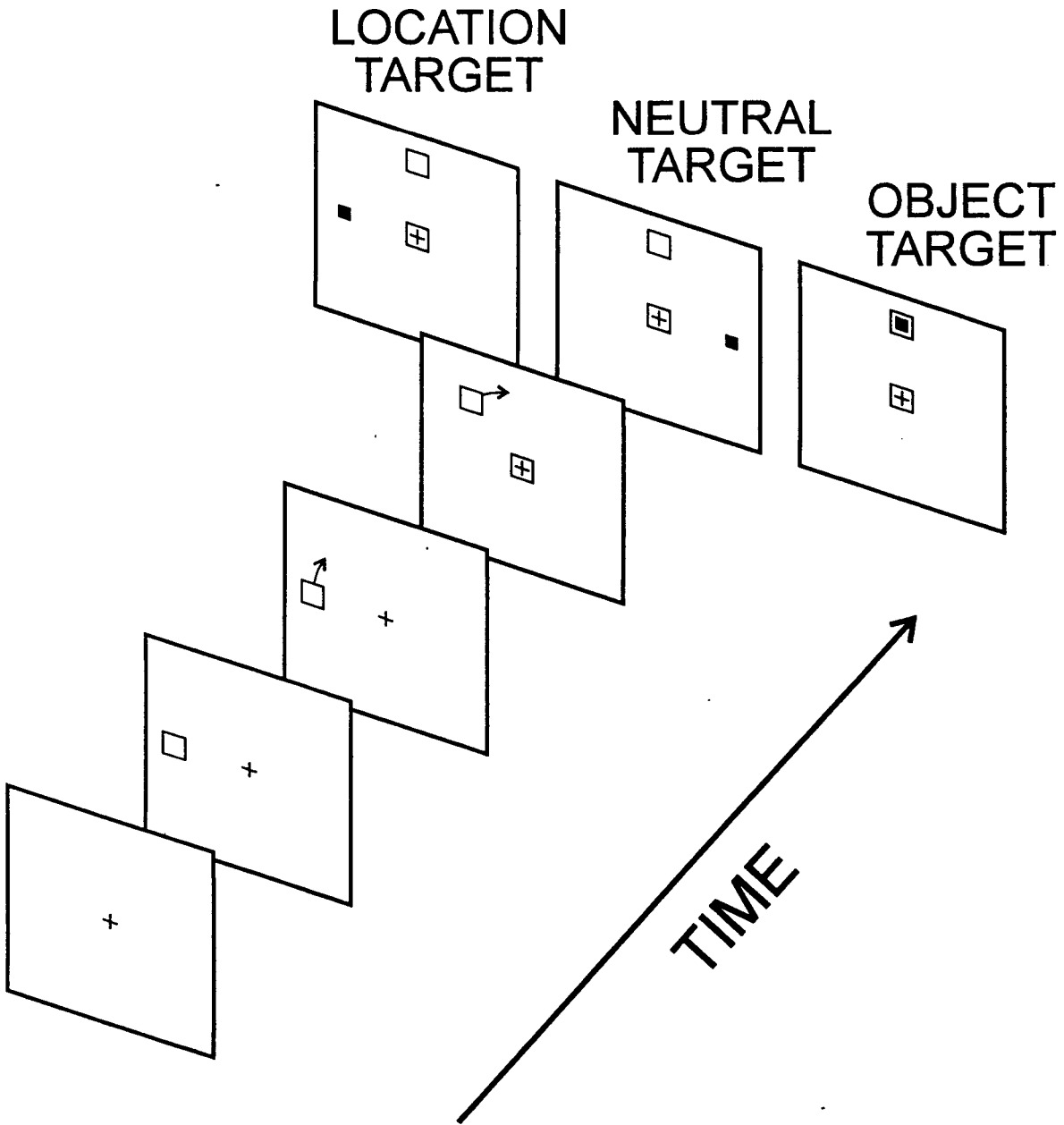
TARGETS TO BE TRACKED

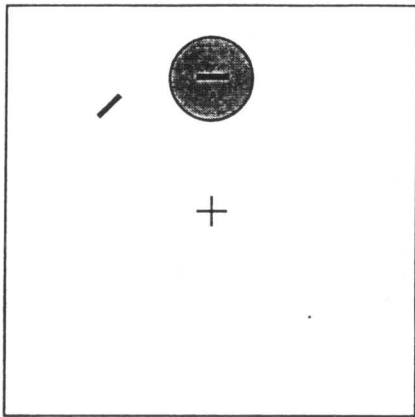


SEVERAL SECONDS OF QUASI-RANDOM INDEPENDENT MOVEMENT

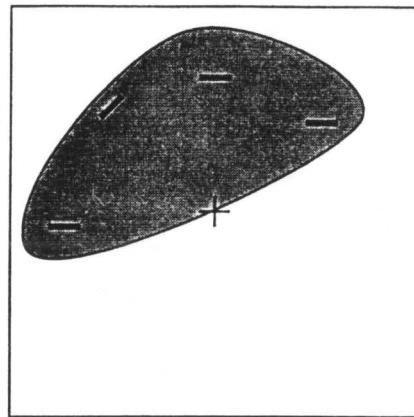


IS THIS ONE OF THE TARGETS ?



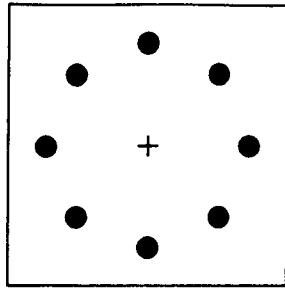


SINGLE-CUE
CONDITION



MULTIPLE-CUE
CONDITION

A



POSSIBLE
CUE/TARGET
LOCATIONS

B

