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Finsting Multiple Places In The Visual Field: Evidence For Simultaneous Facilitation

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FINSTING MULTIPLE PLACES IN THE VISUAL FIELD: EVIDENCE FOR SIMULTANEOUS FACILITATION

by

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Abstract

Indexing of multiple locations in a visual display was examined in the context of a selective search task. Subjects searched for a conjunctively defined target among subsets of display items randomly distributed throughout the display, identified only by their abrupt onset relative to other items in the display. Experiment 1 indicates that search is faster when observers search selectively over a subset of three display items (among a total of fifteen) indicated as potential target positions. Moreover, this result cannot be due to selective attention to one of the indicated items only, because search times are influenced by characteristics of the *set* of indicated items (these same characteristics have no meaning for single items). In particular, search is faster when the selected subset includes only one type of distractor (thus, as a set, the items share only one feature with the target); in contrast, slower search is observed when the subset includes mixed distractors (thus, as a set, the selected items share both features with the target). Experiments 2 and 2b demonstrate that search times are not slowed when the spatial dispersion of the indexed items is increased, discounting hypotheses that one attentional locus is either expanded to include the indicated items, or moved in an analog fashion from item to item. According to the results of Experiments 3 and 3b, observers are able to select up to five items in a display, and the advantage for subsets including homogenous distractors increases with increases in the number of selected items. Taken together, the results of these experiments suggest that observers can select a small number of items in a display (up to four or five) and subsequently

treat these items virtually as if they are the only items that appear. These results are discussed in the context of a theory of visual indexing (FINST theory), which assumes that the visual system uses a small number of indexes (FINSTs) to mediate the engagement of a single attentional mechanism.

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perhaps shape (e.g., Farah, 1989), of the attentional focus can change according to both task demands and the intentions of the observer. These types of changes, however, are generally viewed as the limits of flexibility of the attentional process. The spotlight model (e.g., LaBerge, 1983; Posner, Snyder & Davidson, 1980) and the zoom lens model (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985) each offer variations on the theme of a unitary attentional process, differing in details of the workings of the unitary attentional 'beam'. Despite their differences, the spotlight and zoom lens models of visual attention each retain the fundamental premises that: a) there is one type of attentional facilitation; and b) attentional facilitation can accrue to one and only one contiguous region of the display at any given time.[2] There are, however, empirical challenges to each of these assumptions, suggesting that these models of visual attention may not adequately describe the process.

Attentional Loci: How Many?

The assumption that there can be only one focus of visual attention has been tested by different researchers using different paradigms. Results of these studies have been mixed, and generally interpreted to support the hypothesis of a unitary focus of attention. There have, however, been studies with equivocal results, along with several

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[2] A third attentional theory is the gradient model (e.g., Downing, 1988; Downing & Pinker, 1985; LaBerge & Brown, 1989; Madden, 1992; Shaw, 1978; Shulman, Wilson & Sheehy, 1985). The gradient model allows for the possibility of multiple peaks in the attentional gradient; thus, the model allows for multiple attentional loci. In this respect, the gradient model differs from both the spotlight and zoom lens models. Nonetheless, the gradient model shares with these other models the assumption that there is only one type of attentional facilitation, the model therefore cannot account for evidence that attentional facilitation differs with the type of cuing procedure.

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This thesis investigates simultaneous processing of multiple locations in a visual display. The thesis begins with a review of relevant literature on visual attention, and continues with a discussion of a theory of visual indexing (FINST[1] theory). These two discussions provide a general context for the body of the work, which focuses on a particular implication of the FINST theory. This implication, and the resulting hypotheses, are outlined in the second chapter of the thesis. The third chapter presents information on the experimental methodology, describing aspects of experimental design that are common to all experiments. A series of three experiments (two of which include a primary experiment and a second, control experiment) forms the body of the thesis. In the final chapter, the results of these experiments are discussed in relation to visual attention and a theory of visual indexing.

Background

Most theoretical accounts of attention hold that visual attention is unitary: unitary in the sense that there is a single, undifferentiated process of visual attention; and unitary in the sense that there is, at any given time, a unique focus of that process. It is widely agreed that the size (e.g., Hughes & Zimba, 1985; Laberge, 1983), and

[1]Pylyshyn offers the following explanation of the FINST acronym:

> This rather ungainly name has a marginally relevant history. FINST indexes instantiate internal variables by binding them to elements in a scene in such a way that they remain bound even when the elements move about. Hence they act like fingers, and were whimsically referred to as "FINgers of INSTantiation" (personal communication, August 1993).

perhaps shape (e.g., Farah, 1989), of the attentional focus can change according to both task demands and the intentions of the observer. These types of changes, however, are generally viewed as the limits of flexibility of the attentional process. The spotlight model (e.g., LaBerge, 1983; Posner, Snyder & Davidson, 1980) and the zoom lens model (e.g., Eriksen & St. James, 1986; Eriksen & Yeh, 1985) each offer variations on the theme of a unitary attentional process, differing in details of the workings of the unitary attentional 'beam'. Despite their differences, the spotlight and zoom lens models of visual attention each retain the fundamental premises that: a) there is one type of attentional facilitation; and b) attentional facilitation can accrue to one and only one contiguous region of the display at any given time.[2] There are, however, empirical challenges to each of these assumptions, suggesting that these models of visual attention may not adequately describe the process.

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pieces of research that provide strong evidence of simultaneous attentional facilitation at multiple locations in the visual display.

Driver and Baylis (1989) contrasted the interference effects of two types of distractors. Distractors falling within the same perceptual group, but physically further from the target, produced greater interference than closer distractors that were not included in the perceptual group (but see Kramer, Tham, & Yeh, 1991, for a failure to replicate this result). On the strength of these results, Driver and Baylis suggest that attention is assigned to perceptual groups whose components may be spatially dispersed. This interpretation is inconsistent with the spotlight model, and instead supports a model in which attention can be simultaneously directed to multiple spatially disparate locations in the visual array.

Juola, Bouwhuis, Cooper, and Warner (1991) cued ring-shaped regions around fixation. Their results indicated facilitation within the cued ring and inhibition in uncued rings (including areas *enclosed inside* cued middle and outside rings). Juola et al. explicitly tested alternative models of attentional allocation, including the possibility that observers were serially examining objects in the display, starting with those objects appearing within the cued region. Contrasting a zoom-lens model, a ring model, and a serial search spotlight model, their results were best predicted by the ring model, with the added assumption that, in the absence of instructions to attend to a specific ring, observers allocated attention to the middle and outer rings, assuming that the foveal area would "take care of itself" (this assumption is suggested by the results of Posner, 1980). The results of this study suggest that attention can be deployed in a manner quite unlike that suggested by the spotlight metaphor. In particular, it appears that attention can be allocated to the *edges* of a circular region in space, while the *center* of the same region is excluded from attentional benefit.

In another study, Castiello and Umiltà (1992) found evidence supporting a theory of attentional splitting. Their research demonstrated that observers are able to vary independently the area over which attentional resources are allocated in *two* spatially disparate locations. They examined reaction time distributions to discount the possibility that observers were actually allocating attention to one of the cued locations on each trial. They concluded that reaction time distributions were unimodal (as would be predicted by a hypothesis that attention is split across space within a single trial) rather than bimodal (as would be predicted by a hypothesis that attention is allocated to only one of the cued locations on each trial). Furthermore, they found evidence for attentional splitting only when the attentional cues were objects that defined the areas to be attended, rather than single lines that lay above these areas. This last point is particularly interesting, suggesting that splitting of visual attention might be possible *only* in those situations where there are existing objects which explicitly mark the location and define the spatial extent of each of the multiple desired attentional foci.

The results of Driver and Baylis (1989), Juola et al. (1991) and Castiello and Umiltà (1992) provide strong evidence that visual attention can be simultaneously assigned to non-contiguous regions in visual space. In the cases of Juola et al. and Castiello and Umiltà, this evidence is particularly convincing given that these authors explicitly test, and rule out, the alternative explanation that attention is initially allocated to *one* of the likely locations (or objects) on each trial. There are other studies with results supporting the hypothesis that visual attention can be allocated in a spatially discontinuous fashion; these researchers, however, often fail to rule out completely alternative accounts of the results.

Falling within this class are the studies of Shaw and Shaw (1977), who demonstrated an enhancement in letter identification when the number of potential target locations was reduced from eight to two. This conclusion is suspect, however, because of the possibility that observers were simply attending to one of the two potential target locations on any one trial, without allocating any attention (during that particular trial) to the other potential target location. In a study similar to that of Juola et al. (1991), Egly and Homa (1984) demonstrated attentional facilitation in a ring-shaped area around fixation, without attentional benefit inside the ring. Their results, however, are subject to the same alternative as that presented for the results of Shaw and Shaw. In particular, Egly and Homa fail to rule out the possibility that subjects are simply attending to one of the indicated locations on each trial, thus demonstrating an average benefit for the cued region over a number of trials.

Finally, some researchers fail to find evidence for splitting of attention across two spatially disparate loci. Posner, Snyder and Davidson (1980) used a simple reaction time task to test the hypothesis that attention can be split. Subjects were informed that the target could occur at a primary location (identified at the beginning of the trial) with a probability of .65, and at a secondary location (held constant across a block of trials) with a probability of .25. Posner et al. found facilitation of the secondary location *only* when it was adjacent to the primary location, suggesting that the attentional spotlight could be modified in size, but not split to cover distant locations within the same display. Kiefer and Siple (1987) replicated this result in a detection task using a slightly different cuing method. They precued two locations at the beginning of each trial, each with an equal probability of being the location of a target, and found that this change did not improve the ability of observers to split attention.

Without further research, it is impossible to reconcile completely the findings of researchers who demonstrate a unitary focus of attention (e.g., Posner et al., 1980; Kiefer & Siple, 1987) and those who demonstrate multiple loci (e.g., Castiello & Umiltà, 1992; Driver & Baylis, 1989; Juola et al., 1991). Nonetheless, it is possible to speculate concerning the bases of their seemingly contradictory results.

Castiello and Umiltà (1992) demonstrate the splitting of attention only when there are existing objects that define the areas to be attended. Posner et al. (1980) and Kiefer and Siple (1987) used arrows to direct attention to blank regions in the visual display; thus, in their displays no objects existed, at the time of attentional cuing, to which attentional resources could be allocated. In contrast, Juola et al. (1991) directed attention to a visible contour joining the potential target locations, and Castiello and Umiltà directed attention to pre-existing boxes to the right and left of fixation. Thus, one potential explanation of the contradictory results is the possibility (explicitly tested and confirmed, within their experimental paradigm, by Castiello and Umiltà) that observers can divide attention between multiple loci *only* under the condition that there are existing objects at each location to which resources are to be allocated (see also Intriligator & Cavanaugh, 1992; Pylyshyn & Storm, 1988 and Sears & Pylyshyn, 1991 for evidence that multiple objects in the visual field can be simultaneously and independently tracked).

It appears that it is possible to split attention between two existing objects, but attention cannot be split between two (or more) empty regions of visual space. Thus, at least under some conditions, attention can be split over multiple discontinuous areas within a visual display. This conclusion contradicts the view, endorsed within both the spotlight and zoom lens theories of visual attention, that there can be only one attentional locus.

Types of Attention

The assumption that there is only one *type* of visual attention is challenged by another body of research, examining the effects of two different types of attentional cues. The two types of cues to manipulate the attentional focus are endogenous (or central) cues and exogenous (or peripheral) cues.

Endogenous cues are symbolic cues, usually presented at or near fixation (although they may appear in other regions of the visual field, and indeed may be presented in other modalities, such as sound). It is the interpreted meaning of these cues that is used to direct the allocation of visual attention. In contrast, exogenous cues (usually visual cues; but localized auditory cues have been used, e.g., Shimojo, Miyauchi & Hikosaka, 1992) appear at or near the location to be attended. The location of exogenous cues, as opposed to their interpreted meaning, carries information concerning where attention is to be directed. In many studies of visual attention, endogenous and/or exogenous cues are used interchangeably, without reference to the difference between the two types of cuing. There is, however, a large body of research that suggests the attentional effects of these two types of cues, while similar in some respects, are not identical.

Attentional cuing has been demonstrated to improve accuracy and decrease reaction time in both detection and discrimination tasks; all of these effects have been demonstrated with both endogenous and exogenous cues. Hawkins, Hillyard, Luck, Mouloua, Downing, and Woodward (1990) demonstrated improvements in detection accuracy as a result of both endogenous and exogenous cues. Their analysis suggests that improvement in detection is a result of enhanced sensitivity (d'), along with shifts in decision criteria (β) in some conditions (Bashinski and Bacharach, 1980 reported similar increases in sensitivity, testing endogenous cues only; van der Heijden & Eerland, 1973, also provide evidence for an increase in detection accuracy as a result of exogenous cues). A decrease in detection latency in response to exogenous cues has been demonstrated by Eriksen and Hoffman (1974). Posner, Nissen, and Ogden (1978), along with Eriksen and Hoffman (1974), showed the same effect with endogenous cues. Accuracy of discrimination improves in response to valid cues of both endogenous and exogenous types (endogenous and exogenous cues: Müller & Findlay, 1988; exogenous cues only: Henderson, 1991; van der Heijden, Schreuder, &

Wolters, 1985). Finally, decreases in reaction time for discrimination tasks with exogenous cues have been demonstrated by Henderson, 1991; Shaw and Shaw (1977) provided evidence that the same decreases can be observed under central cuing conditions (see also Warner, Juola, & Koshino, 1990, for evidence regarding discrimination reaction time facilitation with both peripheral and endogenous cues).

Endogenous and exogenous cues are, therefore, similar in that they produce facilitative effects in the same visual tasks. In response to each type of cue, it appears that observers are able to devote attentional resources to indicated areas of the visual display. There is, however, empirical evidence of reliable differences in a number of aspects of the facilitative effects of endogenous and exogenous cues. These differences appear in: the reflexiveness of the cue response; the time course of facilitation; the degree of facilitation; and the presence of inhibition of return.

The attentional response to abrupt onsets appears to be reflexive, in contrast to the voluntary orienting of attention in response to endogenous cues. Jonides (1981) demonstrated that orienting to endogenous cues is completely under voluntary control, and does not occur without the express intention of the observer. In contrast, abrupt onset stimuli (which are by definition exogenously cued) are generally processed before other, non-abrupt onset items in the same display, even when there is no intention to facilitate these items, and no performance advantage to such facilitation.

This processing advantage for abrupt onset stimuli holds even when there is no greater probability that the abrupt onset item will be the target (Yantis & Jonides, 1990). Furthermore, the preferential processing of abrupt onset items occurs when observers are informed that the target will *never* appear at the abrupt onset location (Remington, Johnston, & Yantis, 1992; but see Warner, Juola, & Koshino, 1990, for evidence that this interference from abrupt onset stimuli might be mitigated by practice). Prior knowledge of the abrupt onset location does not allow observers to suppress the response (Remington et al., 1992). Nonetheless, despite the apparent automaticity of the response to exogenous cues, there is one condition under which it is *not* observed. In particular, exogenous cues do not appear to draw attentional resources when those resources have been allocated, prior to the onset of the peripheral cue, in response to a central cue that is *perfectly* predictive of target position (Yantis & Jonides, 1990; note that if the central cue is less than 100% predictive of later target location, reflexive orienting to exogenous cues interrupts response to endogenous cues, as reported by Yantis & Jonides, 1990, and Müller & Rabbitt, 1989).

Researchers (e.g., Müller & Findlay, 1988; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Shepherd & Müller, 1989) have demonstrated that attentional facilitation in response to exogenous cues appears earlier and is stronger than the facilitation in response to endogenous cues. This research shows that attentional facilitation in response to exogenous cues is maximal approximately 100-150 msec after cue onset, fading within 300 msec of the cue. In contrast, the response to endogenous cues shows a gradual buildup, particularly in the first 300 msec after cue onset. Furthermore, these studies show that the early, reflexive facilitation in response to exogenous cues is particularly strong, resulting in greater reaction time and accuracy advantages than facilitation in response to endogenous cues. When exogenous cues are informative (that is, when they accurately identify locations that are likely to contain targets), there is an early peak in facilitative effects followed by a later plateau at a lower level of facilitation (e.g., Müller & Findlay, 1988; Nakayama & Mackaben, 1989). Müller and Findlay (1988), along with Nakayama and Mackaben (1989), have argued that this pattern of results reflects the effects of both early involuntary facilitation (in response to the exogenous cue) and later voluntary facilitation (in response to the information about target location provided by the cue).

Subsequent to an exogenous cue, the area (or perhaps object) that received the benefit of attentional facilitation is inhibited for a short period of time. This effect has been termed 'inhibition of return'. Endogenous cues do not produce inhibition of return (e.g., Posner & Cohen, 1984). Inhibition appears to accrue to the exogenously cued location approximately 500 msec after cue onset, following a brief period of facilitation as described above (e.g., Maylor, 1985; Nakayama & Mackeben, 1989). There is strong evidence that inhibition of return is mapped in environmental, not retinal, coordinates (Maylor & Hockey, 1985; Posner & Cohen, 1984). Thus, it appears that inhibition of return operates to reduce the probability that limited processing resources will be held by a single object in a display, precluding processing of other objects.

The mounting evidence of differential effects and time courses of response to endogenous and exogenous cues forces a modification of traditional attentional theory. In particular, this body of evidence precludes the possibility that endogenous and exogenous cues elicit a single type of spatial attention through a single orienting mechanism. Based on the results of many experiments demonstrating different effects of the two types of cues, it has been proposed that there is one type of attention with two completely different (though possibly interacting) orienting mechanisms (e.g., Jonides, 1983; Müller & Rabbitt, 1989), or that there are two different types of attention elicited by endogenous and exogenous cues (e.g., Briand & Klein, 1987; Nakayama & Mackeben, 1989; Weichselgartner & Sperling, 1987).

There is, however, at least one other alternative. Perhaps there is a single attentional system (maybe even with a single processing locus), together with a limited capacity mechanism that mediates the *engagement* of this attention. This engagement selector, or indexing mechanism, might provide simultaneous potential access to a limited number of locations or objects, with the actual allocation of attentional processing to these locations being made either in parallel or in series depending on the task. Just such a mechanism is proposed in FINST theory (e.g., Pylyshyn, 1989; Pylyshyn, Elcock, Marmor, & Sander, 1978; Pylyshyn & Storm, 1988; see also the work of Yantis and his colleagues on attentional tags, e.g., Yantis & Johnson, 1990; Yantis & Jones, 1991).

It is an assumption of FINST theory that the deployment of attentional resources is necessarily mediated by visual indexes. Under this assumption, differences in the attentional response to endogenous and exogenous cues may reflect differences in the likelihood with which each type of cue engages the selection mechanism (or differences in the methods by which each type of cue attempts to do so). The FINST theory of visual indexing assumes (as outlined in the next chapter) that there are multiple visual indexes. Thus, this theory is compatible with evidence of multiple loci of attentional facilitation. In order to draw the link between existing attention theory and the visual indexing (or FINSTing) process more clearly, it is first necessary to outline FINST theory in some detail.

FINST Theory

At this point, it is important to indicate that this thesis is not intended as a test of the FINST theory, whose strength, in any case, rests on a wide variety of convergent evidence. Rather, the thesis is concerned with one particular implication of the theory, which will be outlined (along with other implications) in this chapter. This discussion of FINST theory is intended to provide the reader with a theoretical background on visual indexing and the FINST hypothesis in particular.

What FINSTs Are (and Are Not)

FINST theory, first proposed by Pylyshyn et al. (1978) and later elaborated by Pylyshyn (1989), suggests that the visual system utilizes a number of indexes (called FINSTs) to individuate locally distinct features in the retinal array, in order that they can be accessed for further visual processing. According to Pylyshyn (1989), FINSTs constitute a

> primitive mechanism capable of individuating and dynamically indexing a small number of features (or feature clusters) in the visual field. (pg. 93)

FINST theory asserts that FINSTs index localized *features*, rather than *objects*; however, the presence of a localized feature logically implies the presence of a localized object of which the feature is characteristic. (For instance, it is impossible to have a discrete area of 'green' in an otherwise white visual field without there being some object in the display that has the characteristic of being 'green,' even if that object is simply a blob of 'green.') Thus, although FINSTs are assigned to locally distinct features in the retinal array, it can equally be said that FINSTs point to particular objects in the visual field. Furthermore, by either account there is the following corollary (noted by Pylyshyn),

> We sometimes speak of FINSTs as indexing *places* in a scene, in order to emphasize that it is feature location rather than feature type that is being indexed. However, it should be kept in mind that the theory only provides for *filled* places to be indexed in this way, not places in a totally empty region of the visual field. (1989, pg. 70)

Thus, FINSTs serve to individuate salient feature discontinuities in the visual array.

Under FINST theory, processes that are performed automatically and in parallel across the visual array do not require (or utilize) the FINST mechanism, in contrast to selective visual attention, which is necessarily mediated by FINSTs. In fact, it is these low-level parallel processes that produce the representation(s) over which salience is computed, and thus on the basis of which FINSTs are assigned. Processes that do not require FINSTs include registration of basic features such as colour, orientation, and movement; in other words, they are "primitive retinal processes [that] produce *feature clusters* automatically and in parallel across the retina" (Pylyshyn, 1989, p. 72). Processing beyond this basic level requires selective attention, and thus must be mediated by FINSTs assigned to a particular feature cluster (or set of feature clusters).

FINST theory, therefore, is not an alternative to widely-held views of visual attention. Instead, FINSTs are proposed as a mechanism which mediates the engagement of visual attention; thus, FINSTs can be thought of as underlying (in functional terms) selective attention. The theory assumes that there are multiple

FINSTs that can be simultaneously assigned to disparate places in the visual array; therefore, at any one time there will be multiple locations to which selective attention can be immediately directed. Furthermore, multiple indexes allow for (without demanding) the possibility that these multiple indexed locations may receive simultaneous processing. Finally, FINSTs provide a way to move attention from place to place in the visual display without scanning, because each FINST provides direct access to its indexed feature. FINST theory, therefore, offers hypotheses concerning the mechanics of the deployment of attention; it is not a theory of attention per se.

At this point, it is important to distinguish the *assignment* of FINSTs from the *maintenance* of individual or multiple FINSTs. While it is an assumption of FINST theory that multiple indexes are assigned to salient feature discontinuities without attentional effort (and possibly in parallel), the theory *does not* require that maintaining these indexes be similarly effortless. As discussed later in this chapter, FINSTs are assigned to the most salient feature discontinuities in a visual array (with salience based on a number of different factors that are processed in parallel without attentional effort). The computation of salience is assumed to proceed automatically and in parallel across the visual array. Thus, the salience map will be continually updated by this automatic process. As long as a particular item retains its status among the most highly salient items in the display, it will retain its FINST.

There are, however, a number of factors that serve to change automatically the relative salience of a particular item over time. The first of these is the reduction in salience as an item 'ages' in the display; that is, the longer an unchanging item has remains in the display, the smaller the impact of its original onset on the computation of salience. There are a number of environmental factors that might change over time and thus change the salience of items affected; for example, a change in local lighting, perhaps by the introduction of shadow, could reduce the brightness, and thus salience, of an item. Events in the visual display could increase the salience of currently unFINSTed feature discontinuities, rendering them more salient than the currently FINSTed items. Finally, there is likely to be noise in the system that computes salience (as there is in any biological system), and that noise will change over time, resulting in temporal variations in computed salience in a static environment. For these reasons, in order to ensure that FINSTs remain assigned to particular items, specific action upon the FINSTs or FINSTed items may be necessary. In other words, the observer may have to work to ensure that the currently FINSTed items maintain their status as the most salient items in the display (perhaps by sending activation *down* the FINST: this possibility is discussed later in this chapter). Consequently, the process of maintaining FINSTs on particular items may be effortful and resource demanding, even if the initial assignment of FINSTs is not.

Similarly, it is likely that, while FINSTs are assigned without effort, the attentional processing of FINSTed locations is effortful. Thus, FINST theory does not require that attentional resources, such as those involved in stimulus identification, be readily split across multiple FINSTed locations; in fact, FINST theory is silent on this issue. In fact, there may be some processes that can be applied in parallel across the set of FINSTs, while other can only be applied to one location at a time. While each assigned FINST offers the *potential* for attentional access to a particular place, it is entirely possible that applying an attentional process simultaneously to more than one of these indexed locations is a very difficult, if not impossible, task for the observer.

How FINSTs Are Assigned

In his discussion, Pylyshyn (1989) makes the following statements about the assignment of FINSTs:

> it seems reasonable that they [FINSTs] are assigned primarily in a stimulus-driven manner, perhaps by the activation of locally distinct properties of the stimulus - particularly by new features entering the visual field. ... In addition, under certain conditions top-down processes may also play a role in specifying which of the potential active features get assigned a FINST. (1989, pg. 71)

FINSTs are assigned on the basis of a global measure of the *salience* of a particular feature discontinuity (see Koch & Ullman, 1984, 1986 for a model of selective visual indexing based on salience). The salience of a particular feature discontinuity is based on information provided by the primitive retinal processes such as segmentation and feature registration. Salience is influenced by the similarity between one feature discontinuity and its neighbours; to the extent that a particular discontinuity is distinct from its neighbours, its salience will be increased (e.g., Joordens & Jolicoeur, 1993). In addition, empirical evidence suggests that new objects in the display (e.g., Jonides & Yantis, 1988; Joordens and Jolicoeur, 1993; Remington et al., 1992), or old objects undergoing some substantial and salient change (e.g., Miller, 1989; Theeuwes, 1991), may be particularly salient, particularly in contrast to pre-existing, unchanging objects.

In general, visual events that are registered automatically by the visual system (such as abrupt onsets or object movements; but not colour changes, as demonstrated in Burkell, 1986) have a high degree of salience.

Furthermore, research suggests that observers can restrict FINST-mediated processing to those items sharing a desired feature (e.g., colour, or location in the visual field: see Egeth, Virzi, & Garbart, 1984; Folk, Remington, & Johnston, 1992; and Green & Anderson, 1956). This selective processing could be mediated either by a bias introduced into the assignment of FINSTs, or a by a mechanism that allows fast filtering after FINSTs have been assigned.

Under the first proposal, top-down control could bias the assignment of FINSTs to *particular* feature discontinuities, specified by location or some other simple property. Thus, top-down processes might change the weight assigned to some property (e.g., 'green') in the computation of salience, or selectively enhance the input of one feature map over another, in Treisman's and Gelade's (1980) terms (this proposal is consistent with the Guided Search Model, presented in Cave & Wolfe, 1990; Wolfe, Cave & Franzel, 1989; and Wolfe, 1992,[3] as well as the theory of visual search described by Duncan & Humphreys, 1989). Alternatively, it is possible that the functional locus of selection is *after* the FINST has been assigned on the basis of automatically computed salience. At this point, assigned FINSTs may be quickly

[3]The Guided Search model proposes that weighted outputs of the feature registration process are summed (with greater weights assigned to target characteristics) to create an 'activation map'; the serial identification process is then guided to the location with the highest activation. FINSTs are a mechanism capable of realizing the Guided Search model. In addition, FINSTs account for a number of other empirical observations, including the ability to simultaneously track multiple moving objects.

polled for their value on the relevant property, and dropped if they are not, for instance, the required colour. At the present time, there is no empirical reason to prefer one proposal over the other; it is only necessary to postulate some mechanism that supports selective processing of items based on specific properties.

It is also assumed that a signal can be sent *down* the FINST, changing the input (in all relevant feature maps) from a particular location into the computation of salience. This signal could be of an inhibitory or excitatory nature; the former could realize the empirical phenomenon of inhibition of return (e.g., Maylor, 1985; Posner & Cohen, 1984), while the latter would allow observers to 'hold' a FINST to a particular feature discontinuity for further processing.

Finally, it is necessary to postulate some property of FINSTs that would support the everyday perception of complex visual scenes which include many more feature discontinuities than there are available FINSTs. In the absence of an explicit intention to perform a particular task over a visual scene, we automatically process much of the available visual information, identifying objects and performing other relatively complex (and presumably attention-demanding) processing; presumably, this processing is mediated by FINSTs. If, in the absence of top-down influences, FINSTs were assigned *and remain assigned* to the most salient features in the display, only the most salient objects in the display would receive the visual processing (including identification) that is mediated by FINSTs. It is clear, however, that many (if not all) objects in every scene receive some degree of processing beyond the simple acknowledgement of their presence. Therefore, even without explicit instructions to reassign the small number of available FINSTs within the display, FINSTs must be automatically reassigned in such a way that many objects receive some degree of FINST-mediated processing. This requirement could be satisfied by the assumption that salience is continuously recomputed, changing with noise in the system as well as alterations in the visual stimulus and changing intentions of the observer. At any time, the set of FINSTs would be assigned to the set of most salient objects in the display; without particular facilitation of a salient object, it is likely (through natural factors) to lose its salience and thus its FINST. It is also possible that the salience of a FINSTed feature discontinuity is reduced (by sending inhibition down the FINST) once that FINST has been visited by the selective attentional process.

Koch and Ullman (1986, 1984) present a model of shifts in selective visual attention that is compatible with the FINST hypothesis (Acton, 1993, is currently developing a similar model of visual indexing that supports the assignment of multiple indexes within a single display). In their model, Koch and Ullman suggest that movements of visual attention from a currently selected location to another location are based on a global computation of object salience, which proffers the most salient location in a visual display as the target for the attentional shift. According to Koch and Ullman, the saliency map combines the information of individual feature maps (e.g., maps of 'green') into a global measure of object conspicuity. Koch and Ullman (1984) further suggest that there is

> a "switch" that routes the properties of a single location, the *selected* or *attended* location, into the central representation, which will now contain information relevant to the selected location. (p. 4)

An equally likely mechanism is a "line" that can be pulsed to activate information about the location to which it is attached; it is also possible to envision a pointer (or index) that provides selective access. Under any of these descriptions, the proposed mechanism instantiates the important qualities of a FINST: it provides direct and immediate access to indexed properties without explicitly coding the identity of the properties or their location. These types of indexes would support queries about the feature, and also serve as pointers to these specific features, mediating the engagement of selective attention.

Assumptions of the FINST Theory and Related Empirical Evidence

In his discussion, Pylyshyn (1989) outlines two properties of the FINST mechanism for which there is empirical support. The first is the assumption that there are at least two FINSTs available for use by the visual system (it is also assumed that the total number of FINSTs is limited, although Pylyshyn makes no clear predictions about the upper bound). The second assumption is that the FINST mechanism provides direct access to indexed retinal features (perhaps in a serial manner) without the need to move a unitary focus of attention continuously across the visual field.

Evidence for Multiple Indexes

The initial empirical support for the existence of FINSTs arose from multiple target tracking experiments (e.g., Pylyshyn & Storm, 1988). In these experiments, observers are asked to track simultaneously a prespecified subset of a larger number of identical, randomly moving objects in a visual display. The members of the subset to be tracked are identified, prior to the onset of movement, by some characteristic but transient property (e.g., the items to be tracked may flash for a short period of time, or undergo a transient change to some distinctive colour). Experiments using the tracking paradigm (e.g., Pylyshyn & Storm, 1988) have demonstrated that observers are capable of tracking approximately five distinct objects without eye movements. Pylyshyn and Storm explicitly ruled out alternative explanations for this ability to track multiple items, including the possibility that observers maintain a 'list' of object locations, updating the stored location of each object when a single attentional beam (moved from object to object) is focused on that particular object.

Other evidence for multiple loci of attention arises in the investigation of the facilitation of abrupt onset items. Although the FINST theory does not explicitly predict a processing advantage for abrupt onset items relative to other items in a display, the theory does postulate that items cannot be candidates for further visual processing *unless* there is a FINST assigned to the item. Furthermore, it is an assumption of the FINST theory that, in the absence of top-down influences, FINSTs are assigned in a stimulus-driven manner in response to locally distinct and salient stimulus features (abrupt stimulus onset would satisfy these criteria). Thus, the theory implies that abrupt onset items would automatically be assigned FINSTs (unlike other, less salient stimuli in the same display). Given that a FINST must be assigned to an item before attention can be directed to it, abrupt onset stimuli would receive selective processing that is mediated by FINSTs (including stimulus identification) prior to other stimuli. This hypothesis leads to the prediction that abrupt onset items will be processed more quickly (and perhaps more accurately) than other, non-abrupt-onset, items in the same search display.

Yantis and his colleagues have investigated the visual processing of abrupt onset items in a search task, showing consistent reaction time advantages for abrupt onset targets. Using a terminology different from that of Pylyshyn, Jonides and Yantis (1988) write of 'attentional priority tags' that are involuntarily assigned in response to abrupt onsets. According to the results of Yantis and Johnson (1990), there are approximately four of these attentional priority tags, a number that is close to the five independent objects that can be simultaneously tracked in the multiple target tracking experiments (Pylyshyn & Storm, 1988). Yantis and Johnson (1988) also demonstrate that the degree of facilitation for abrupt onset items decreases over time. This evidence is consistent with the assumption that attentional tags (or FINSTs) tend to 'move on' after a period of time, at least in the absence of explicit maintenance of the index through intentional, cognitively-driven attentional mechanisms.

Evidence for Direct Access to Indexed Retinal Features

In support of anothe: prediction of FINST theory, several authors (e.g., Eriksen & Webb, 1989; Kwak, Dagenbach, & Egeth, 1991; Remington & Pierce, 1984; Rizzolatti, Riggio, Dascola, & Umiltà, 1987; Sagi & Julesz, 1985a, 1985b) have found evidence that attention can be shifted between salient objects in the visual display in a length of time that is independent of the distance between the two objects (see also

Shepherd & Müller, 1989 for a compatible result placed in the context of a gradient theory of attention). In these experiments, objects were salient either by virtue of spatial precuing (Eriksen & Webb, 1989; Kwak et al., 1991), or by virtue of the fact that they were the *only* objects in the display (Sagi & Julesz, 1985a, 1985b). Thus, in every case, there were objects at the target location to which a FINST could be assigned; according to FINST theory, these indexes would facilitate immediate shifts of attention.

The conclusion of time-invariant attentional shifts, however, has not gone unchallenged. Shulman, Remington, and Maclean (1979) found evidence for analog movement of attention, as did Tsal (1983), and Egly and Homa (1991). The investigations of Tsal, and Shulman et al. have been criticized on different grounds (see Eriksen & Murphy, 1987[4], and Yantis, 1988). Furthermore, Shulman et al. employed central cues to direct attention to an empty region of the visual display, demonstrating facilitation (for simple reaction time to luminance onsets) for spatially intermediate locations at a time prior to maximal facilitation for the target location. FINST theory, however, assumes that FINSTs cannot be assigned to empty regions in space; the endogenous cues in this experiment directed attention to a region that *did not* contain an object. Under these conditions, there could be no FINST assigned to the indicated location (since there is no feature discontinuity to which the FINST could be assigned), and thus there is no FINST to facilitate immediate access to the cued

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[4]Note that Eriksen and Murphy also criticize the conclusions of Remington and Pierce (1984), who present results supporting time-invariant shifts of attention.

location. Therefore, it appears that the strongest body of evidence supports time-invariant shifts of attention between *occupied* locations, supporting the hypothesis of direct access to indexed locations.

FINSTs and Attentional Effects

Abrupt onset of objects, it has been argued, makes those objects salient, and thus prime candidates for the assignment of a FINST. If a FINST is assigned to an object by virtue of its abrupt onset, that object may have a 'head start' when it comes to further processing (such as identification). The FINST provides the reference (or pointer) necessary for the application of the attentional process. When the reference is in place before there is a demand for processing, a reaction time advantage may be observed because one step in the sequence of events required for further visual processing has been completed. Thus, exogenous cues result in attentional facilitation because they provide appropriate places for attention to 'go,' through a primitive indexing mechanism.

Experiments using central cues, on the other hand, generally direct the attention of the observer to empty locations in visual space. FINSTs cannot be assigned to empty regions: a FINST must have a feature or property discontinuity to which it can 'attach' itself. It is possible that, in response to a central cue, the observer can enhance the input of a general region to the global computation of salience (though this region may have to be specified relative to the current locus of attention). Alternatively, assigned FINSTs could be quickly filtered on the basis of the region in which they appear, allowing FINSTs indexing unwanted locations to be quickly dropped. Either of these mechanisms would have the effect of enhancing the likelihood that objects later appearing in the facilitated region would retain a FINST. Thus, in response to a central cue, it may be possible to increase the probability that FINSTs will later be retained by objects within the cued region; when no object currently exists within this region, however, the actual assignment of the FINST must wait until an object appears.

Why should the facilitative effect of abrupt onset cues decline after a short time? It is assumed that a FINST will be assigned in response to the abrupt onset of a stimulus. Initially, the cue has increased salience by virtue of its recent abrupt onset. The longer the cue remains in the visual display without changing, the smaller the effect of its onset on the computation of salience. Therefore, as time passes after the cue onset, it becomes more likely that the cue will lose its relatively high degree of salience, and thus lose its FINST. As more time elapses between cue onset and further processing, there is an increase in the probability that the FINST will 'move on' to another, more salient feature discontinuity (i.e., be attracted to another feature).[5] Of course, it is not postulated that the decision to move to another object rests with the FINST itself; instead, it is assumed that the salience of objects in the display is being

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[5]In fact, there are at least three options for de-FINSTing:

(1) spontaneous decay over time - or an increase in the probability of spontaneous loss

(2) interference, and thus an increase in the probability that another salient item will draw the FINST away

(3) a combination of (1) and (2).

continually recomputed. As an object 'ages' in the display (and nothing else happens to increase or maintain its salience) the object becomes less salient, and thus less likely to retain the FINST that has been assigned to it. If an object (or a cue) loses its FINST, it will no longer demonstrate the processing advantage that results from the prior assignment of a FINST. Thus the facilitation in response to exogenous cues will decrease as the temporal gap between cue onset and target onset increases.[6]

FINST theory is capable of explaining the observation that facilitation in response to exogenous cues is both stronger and faster than facilitation in response to endogenous cues. Other differences in the response to endogenous and exogenous cues can be accommodated within the FINST perspective as well. Inhibition of return would be predicted by the assumption (mentioned above) that the salience of objects is reduced or inhibited once that object has been processed.

It is also possible, within the FINST perspective, to account for the reflexive response to exogenous cues (in contrast to the voluntary response to endogenous cues). It has been reasoned that the salience of abrupt onset items will be automatically enhanced; from the perspective of ecological validity, it seems that new items in the display (as harbingers of hitherto unavailable information) must be granted a greater

[6]Of course, in many peripheral cuing experiments, the cue is displayed for a short time only, and then disappears. In this case, later facilitation of the cued location cannot result from a FINST that maintains its assignment to an enduring object in the visual array. It is, however, possible that FINSTs may be assigned to a more central locus, such as a buffer. In our everyday experience, it is not uncommon for a given object to become invisible for short periods of time (the object may be occluded by another, or it may move off the retina as a result of movement of the eyes or the person: see Pylyshyn, 1989 for a discussion of FINST 'stickiness' in just this situation). It is arguable that an object reappearing after a short absence *should not* be treated as a new object by the visual system, because this would result in a great deal of unnecessary specialized processing for pre-existing objects.

likelihood of receiving some degree of processing beyond simple acknowledgement of their presence. It has also been reasoned that observers may be able to influence the input of particular qualities to the computation of salience, or quickly filter FINSTs after they have been assigned, in order to bias FINSTs towards particular items in the display. This second type of influence over salience (which is the type of influence engaged in response to endogenous cues) is under voluntary control. It is not the case that, for example, 'green' items should (on a general basis) be particularly interesting to the visual system; nor is it the case that, as a basic premise of visual processing, particular salience should be assigned to objects appearing, for example, to the left of fixation. These types of definitions of 'interesting' items will, from time to time, be important to the optimal performance of a particular task. As a general rule, however, such preferences would create odd and possibly detrimental patterns of visual processing (consider, for instance, the life expectancy of a rabbit who can be counted on always to process objects - including predators - appearing to the left of fixation before those appearing to the right of fixation!). Thus, the probability that a FINST will be assigned (and remain assigned) to a particular feature discontinuity should be *reflexively* enhanced in response to object onsets and other salient object attributes, and *voluntarily* enhanced in response to other directives.

Summary

The FINST theory of visual indexing, as outlined in this chapter, proposes a mechanism that is used to direct visual attention (as it has traditionally been viewed).

It appears that a theory of visual indexing can account for many of the observed differences in the processing of endogenous and exogenous cues. Furthermore, it is a requirement of FINST theory that there are multiple FINSTs, and thus multiple loci of any facilitation that results either from FINST assignment or from processes that can be applied in parallel across FINSTed locations. FINST theory is therefore compatible with evidence for multiple loci of attention.

As noted earlier, FINST theory is not intended as an alternative to existing models of selective attention. Instead, FINSTs are proposed as mechanisms that mediate the engagement of a selective attention process. FINST theory is entirely compatible with a hybrid model of attentional processing in which the FINST mechanism indexes salient places in the visual array, allowing the engagement of selective attention at those places. A modification of either spotlight or zoom lens theories of attention to accommodate visual indexing would allow either model to explain results that would otherwise fall outside the theoretical predictions.

This thesis, however, is not intended as a test of an attentional model that incorporates visual indexing into a spotlight or zoom lens theory. Neither, as indicated at the beginning of this chapter, is this thesis intended as a general test of the FINST theory. Instead, the thesis investigates one particular claim of FINST theory. In the next chapter, the relevant claim is identified, along with resulting hypotheses that are addressed in this research.

Experimental Hypotheses and Issues of Experimental Design

Experimental Hypotheses

This thesis investigates one particular claim of FINST theory, namely the claim that the visual system has a means to make a set of non-contiguous features readily accessible to further processing. The FINST mechanism allows a number of independent places to be indexed so attention can be directed to those places without the necessity of first carrying out a visual scan. The result should be that subjects in visual search tasks can behave as though the indexed items are virtually the only ones in the display. This result, if true, is incompatible with traditional spotlight and zoom lens theories of attention, which are the received wisdom.

This is the only aspect of the FINST theory that is investigated in this thesis. However, there is at least one spinoff prediction that FINST theory makes if we assume that abrupt onset items automatically attract indexes. If these items are indexed, and therefore the need to scan for them is obviated, there is no expectation that indexed items that lie further apart should require more time to locate. Consequently, in contrast with predictions of spotlight and zoom lens attention theories which require analog scanning, FINST theory suggests that search time among indexed items should not increase with the dispersion of these items.

Design of Experiments

Conjunction Search

The experiments included in this thesis use the conjunction search task (Treisman & Gelade, 1980) to investigate processing over an indexed subset of items in the visual array. In the conjunction search task, subjects are instructed to search over a set of distractors for a target item defined by a particular conjunction of features (e.g., green and left diagonal). The features represented in the distractor set determine the difficulty of the search task. If the set of distractors taken together includes only one of the features of the target item (e.g., red and *left diagonal* distractors with a green and left diagonal target), then search is effortless, fast, and reaction times are virtually independent of the number of distractors in the display (it has been argued that this type of search is parallel). If, however, the set of distractors includes both features of the target item (e.g., the target could be green and left diagonal, with a set of distractors including both *green* right diagonal items and red *left* diagonal items), then search becomes effortful, slow, and reaction times are dependent on the number of distractors in the display (under these conditions, search is sometimes assumed to be serial; Treisman & Gelade, 1980). Displays of the first type (homogeneous distractors, which include in the set only one of the two defining features of the target) are termed *feature search* displays, while displays of the second type (mixed distractors, which include in the set both defining features of the target) are termed *conjunction search* displays.

Treisman and Gelade suggest that the decision about target presence/absence in a feature search display is made on the basis of a fast, preattentive process that automatically registers the types of features present in a display. Thus, in a target-absent feature search display, where the target is a green left diagonal and distractors are red left diagonals, this preattentive process would register the presence of 'red' and 'left diagonal.' Since one of the features necessary to define a target is absent from this list of features (i.e., there is no 'green' in the display), it is impossible for the display to include a target, and the subject should be able to immediately and accurately respond 'no target.' In contrast, consider a display which includes both red, left diagonal distractors and green, right diagonal distractors (once again, the target is a green, left diagonal element). Under these conditions, the preattentive process will register the features 'red,' 'green,' 'left diagonal,' and 'right diagonal' across the set of items. Since both of the features necessary to form a target ('green' and 'left diagonal') are registered by the preattentive process, and since it is possible for both of these features to be present in the display without characterizing a single object (and thus forming a target), a decision about target presence/absence cannot be made on the basis of this preattentive process. Instead, according to Treisman and Gelade, observers must carry out an item-by-item serial search, checking the particular combination of features that constitutes each object in order to determine if that object is indeed a target.

In the experiments described in this thesis, subjects search for conjunction targets, defined as a particular combination of colour and orientation, among sets of distractors that are, in most cases, mixed, thus including both features of the target. Each search display in this series of experiments (with the exception of two conditions in Experiment 1) contains all of the features necessary to form a target (although not necessarily in the right combination). Target detection in these displays should therefore demand the slow, effortful and possibly serial conjunction search described in the search literature. In most of the displays, a subset of items is cued by virtue of the late onset of the items in the subset relative to the other items in the display (this cuing procedure is described in more detail later in this introduction). In all experiments, subjects are encouraged to restrict their search to the indicated subset of items.

The cuing procedure allows for the manipulation of type of subset (feature subset versus conjunction subset) within displays that include a larger number of mixed distractors. When a smaller number of items are cued within a larger set of items, search reaction times should decrease if subjects are able to use this cuing information to restrict their search to the indicated items. In addition, if observers are indeed able to treat indexed items as if they are the only items in the display, search should be faster among feature subsets than among conjunction subsets. Thus, the incorporation of the cuing procedure in a conjunction search task allows a strong test of the hypothesis that cued items can be selectively processed.

No-Onset Stimulus Presentation Procedure

All of the experiments discussed in this thesis use a variant of the no-onset presentation procedure developed by Todd and Van Gelder (1979). In this procedure, the location of an object is marked, prior to its appearance, by a 'place holder' made up of contours that include all of the line segments of the object, plus other line segments that mask the identity of the object. In Todd's and Van Gelder's paradigm, each place holder is a block figure 8 (two squares stacked on top of each other). When the search stimulus is to be displayed, a number of segments of the figure 8 drop out, revealing a letter in the location previously occupied by the place holder.

With the no-onset presentation procedure, stimulus location can be marked before stimulus identity is revealed, and the onset of the search display need not be coincident with the onset of new objects in the display. In the current experiments an attempt is made to control the assignment of FINSTs to the objects in the display; the no-onset procedure becomes particularly important in this case.

As discussed above, empirical evidence suggests that object onsets automatically attract FINSTs. In traditional search experiments, the onset of the search display involves a large number of abrupt object onsets. Each item of the search display is therefore particularly (and equally) salient, by virtue of its recent onset, in the competition for one of the limited number of available FINSTs. When the onset of the search display is dissociated from object onsets, greater control can be exerted over which objects in the display receive FINSTs. In particular, using the no-onset procedure, some objects can appear earlier than others without allowing early processing of the identity of those items. As time passes after their early onset, the 'new item' salience attributed to these items will naturally lapse. When the members of the cued subset appear some time later, they will be the only items in the display with increased salience by virtue of their recent onset. Thus, search displays can be constructed so that a specially chosen subset of items are the items most likely to be marked by the small number of available FINSTs, without reducing (relative to early-onset items) the time available to process the identity of the late-onset items.

In the current experiments, the place holders are white X's, and the search displays consists of coloured diagonal lines. Prior to the appearance of the search display, the locations that will contain objects are marked by these white X's. The onset of the search display is accomplished by dropping one diagonal of each X and simultaneously changing the colour of the stimulus to either red or green (each approximately equal in luminance[7] to the white of the figure X).

Display Sequence

Throughout the entire set of experiments, observers are instructed to search selectively over an identified subset of the objects in the search displays (in some cases, the subset comprises the entire set, but usually the subset has fewer members than the entire set). Each object in every search display first appears as a figure X

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[7]The red, green and white were set to approximate equiliminance using the minimal border technique (Boynton & Kaiser, 1978). Three observers participated in the luminance matching, setting the luminance of the red and green to match the luminance of the white, which was held constant. For all experiments in the thesis, the luminances of the red and green were set to the average of the points of subjective equiliminance for these three observers.

place holder, and later changes to a coloured diagonal line (one diagonal of the X disappears, and the remaining diagonal changes colour to become either red or green). The members of the selected subset are identical to unselected items in every respect except for the time of their onset (described below).

A typical trial proceeds as follows. At the beginning of the trial (time = 0), a warning tone is sounded (subjects are instructed to focus on the permanently displayed central fixation cross at the time of this warning beep). Five hundred milliseconds later (time = 500 msec), the uncued or early appearing place holders appear. One second after the appearance of these early place holders (time = 1500 msec), the place holders marking the cued items appear. The full set of place holders is displayed for one hundred milliseconds (until time = 1600 msec), at which point each of the place holders changes to a coloured diagonal line. This changed display is the search display, which remains visible until the subject responds. Figure 1 shows the sequence of events on each trial.

The interval between the onset of the cued subset of X's and the change to the search display is within the range providing optimal cuing effects, as demonstrated by previous research on peripheral cuing (e.g., Posner, 1980; Posner et al., 1979)

Experimental Task

The task in these experiments is a conjunction search task. The target, defined as a particular combination of colour (red or green) and orientation (left or right diagonal), is randomly selected for each subject. Subjects are instructed to search for

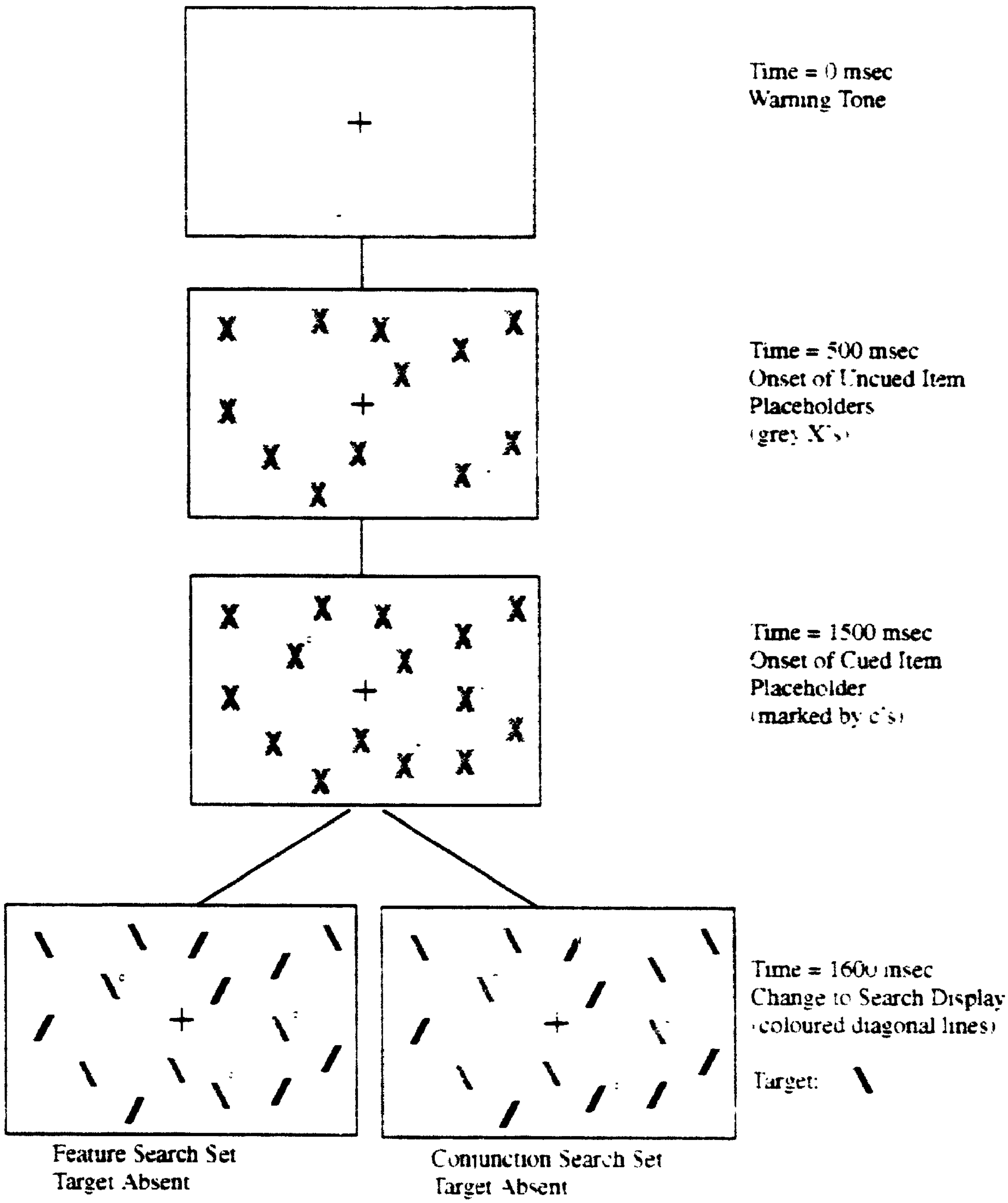

Figure 1. Display sequence for all experiments.

a single target among a variable number of distractors, usually included among a set of items selected from the larger group by the no-onset cuing procedure described above. Each distractor (both cued and uncued) shares either colour or orientation with the target.

The purpose of these experiments is to explore whether (and how) observers are capable of using multiple FINSTs. To this end, in all experiments observers are instructed to attend specifically and solely to the late-onset objects. Observers are accurately informed that targets, if present, will always be among the late onset items. Thus, they correctly believe it is in the interest of optimal task performance to process selectively the cued items. All experiments use experienced observers, and the trials within each experiment are blocked by various independent variables, including search set type.[8]

[8]The practice of blocking trials by search set type is common to most research on visual search (e.g., Treisman & Gelade, 1980). The use of experienced subjects is not so widely practiced. Previous studies in our own lab, however, have shown the difficulty of maintaining multiple indexes, and the importance of practice in learning to do so (e.g., Pylyshyn & Storm, 1988; Sears & Pylyshyn, 1992). Therefore, the current set of experiments combine the standard blocking of conditions with the use of experienced subjects to ensure interpretable results. In any case, Experiment 1 uses exactly the same procedures (that is, blocking and the use of experienced subje ts) for both cued and uncued conditions. Therefore, it will be possible to directly compare selective (cu. .) and regular (uncued) visual search performance under conditions of both blocking and experience to determine if performance is similar in the two types of search.

Experiment 1: Search Among an Indexed Subset

In Experiment 1, subsets of objects in a conjunction search display are cued using abrupt onset. The effects of this manipulation on search performance are examined. Previous research has addressed the relationship between exogenous cuing and the conjunction of features to form object percepts. Treisman and Schmidt (1982) found that the incidence of illusory conjunctions was reduced significantly by the abrupt onset of a single location cue (indicating one of four possible locations of single objects) 150 msec before the onset of the experimental display. Briand and Klein (1987) extended this result, demonstrating that the abrupt onset of a location cue (indicating the spatial location in which an array of two letters would appear) 80 msec before stimulus onset facilitates conjunction search to a greater degree than feature search. Neither experiment, however, addressed the effects of multiple, spatially disparate abrupt onsets on conjunction search performance. Furthermore, neither experiment examined the effects, for the conjunction search task, of selecting a subset of display items. Experiment 1, therefore, offers the following direct extensions of work examining the effects of cuing on conjunction search. First, this experiment uses *multiple* abrupt onset cues at disparate locations in the visual field; second, the effect of multiple cues will be assessed *in the context of other, uncued items.*

Generally, the time required to perform a conjunction search varies linearly with the number of items in the display (e.g., Treisman, Sykes & Gelade, 1977). It has been suggested, however, that search can be restricted to a subset of display items, selected on the basis of a particular quality (e.g., colour, as demonstrated by Green & Anderson, 1956, or form, as demonstrated by Egeth, Virzi, & Garbart, 1984).

In this experiment, late onset is the stimulus quality that identifies items to be selected. It is expected that the abrupt onset of selected objects in the display will serve to increase the salience of those objects, and thus increase the likelihood that each will receive one of the limited number of available FINSTs. Earlier research (e.g., Jonides & Yantis, 1988; Yantis & Jonides, 1984) has shown abrupt onset to be a particularly strong attentional cue; furthermore, attentional benefits accrue to multiple abrupt onset items in a display (Yantis & Jones, 1991). Thus, there is reason to believe that the multiple abrupt onset items in these displays will each be highly salient, and each therefore should be a strong candidate for FINST assignment.

When the total number of objects in the display is larger than the number of abrupt onset objects, the abrupt procedure can be used to identify a subset of display objects. Abrupt onset, unlike colour or orientation, does not in itself define an enduring quality that might be used to identify quickly members of the selected subset as they become the focus of serial processing. When abrupt onset is used to mark items to be selected, it is only the time of their onset (relative to the other objects in the display) that identifies selected objects. 'Time of onset' is not a stimulus quality that endures over time; therefore, in order for selective processing to occur, these late onset objects must be marked (or indexed) when they appear.

The use of a cuing method that is not based on an enduring feature of the objects and the extension of cuing to include more than one object in a conjunction search task allows for the manipulation of characteristics of the cued set of objects. When the cues indicate a subset of objects it is possible, within search displays including exactly the same roster of objects, to contrast search within a *feature search subset* (homogenous distractors) with search within a cued *conjunction search subset* (mixed distractors). That is, given exactly the same objects (e.g., eight distractors of one type and seven distractors of the other type), it is possible to select different *subsets* satisfying the feature versus conjunction distinction. A feature search subset would include three identical distractors (or two plus a target) from among the set of objects, while a conjunction search subset would include one distractor of one type, and two distractors of the other type (or one of each type plus one target).

According to Feature Integration Theory (FIT; Treisman & Gelade, 1980), the features present in each display are registered automatically by a preattentive process. There are two conditions under which this feature registration process would support a decision about target presence or absence: 1) when only one of the features necessary to form a target is represented across the entire display (thus, if the target is a *red left diagonal*, and all items are *green*, then, no matter what orientations are represented among the set, there cannot be a target among those items because there is no item of the correct colour); 2) when both of the features necessary to form a target are present in a display (thus, if the target is a *red left diagonal*, the feature registration process indicates the presence of both *red* and *left diagonal*) and, for one dimension (either colour or orientation) the feature registration process shows that *only* the target value is present (that is, the process indicates the presence of *red*, *left diagonal* and *right* *diagonal* -- at least one object among the set must be both red and left diagonal, because all objects are red and at least one is left diagonal). These two situations are realized in the target absent and target present conditions (respectively) of a feature search display (that is, a display which includes only one type of distractor). When the display includes distractors of both types, it follows that all features necessary to form a target (that is, the target colour and the target orientation) are represented in the display; at the same time, the feature registration process indicates the presence of at least one non-target value for each dimension (that is, a colour that is not the target colour and an orientation that is not the target orientation). Under these conditions, the preattentive process postulated in FIT cannot resolve the question of whether there is a target present in the display, since some items do not share the colour of the target and some do not share the orientation of the target (and the parallel process cannot identify if there is any single item satisfying both criteria). According to FIT, when the parallel feature registration process cannot determine target presence or absence (exactly in the case when the distractors are mixed), a serial search process takes over, scanning each item in turn to determine if it matches the target on both relevant dimensions.[9]

[9]Other theories, including the Guided Search model of Wolfe et al. (1989) and a model of visual search by Duncan and Humphreys (1989), have been proposed to account for visual search results. These models differ from FIT in their explanation of search effects. All models, however, require a stage of parallel processing (either feature registration in FIT and Guided Search, or parallel perceptual description in the model of Duncan and Humphreys). Furthermore, in every case this parallel processing stage is instrumental in accounting for the feature display advantage.

Using the cuing procedure it is possible to identify accurately a subset of display items among which the target (if present) must appear. When this occurs it should be possible for the indicated items to be selected and treated as if they are the only items in the display. If cued items do act as if they are alone in the display, there is evidence that the use of indexes facilitates fast and easy access to information about individual features (but not the conjunctions of features) through a process analogous to preattentive feature registration. This process would, by the reasoning applied above, mediate search among a subset including homogenous distractors (feature search sets) that is faster than search among a subset including mixed distractors (conjunction search sets). For example, search for a 'red, left diagonal' target in a fifteen-item display including eight 'red, right diagonal' distractors and seven 'green, left diagonal' distractors would be faster if three distractors of one type (e.g., three 'red, right diagonal' distractors), rather than three distractors of mixed types (e.g., one 'red, right diagonal' distractor and two 'green, left diagonal' distractors), were indicated as potential targets.[10]

It is important to explicate exactly how this prediction differs from the prediction of FIT. According to FIT, features (but not conjunctions of features) are registered in parallel *across the entire display*. Subsets of items can be selected, from displays including both types of distractors, that satisfy either the feature search set (homogeneous distractors) or the conjunction search set (mixed distractors) definition.

[10]For reasons identified above, the interpretation of these experimental results does not depend on reference to FIT, rather than some other model of visual search. For simplicity of presentation, however, this discussion is referenced to a single model of visual attention (FIT).

Nonetheless, under both conditions, the entire display includes both types of distractors. A feature registration process that operates over the entire display would not, under either the feature search subset or the conjunction search subset conditions, be able to resolve the question of whether a target was present among the cued set. A feature search set versus conjunction search set difference in the current experiment, therefore, would depend on the *selective* registration of features across the cued subset of items.

An equally important point is the following. Demonstration of a difference between processing of feature search sets and conjunction search sets would indicate that observers are FINSTing *more than one* of the items in the indicated subset, rather than simply marking (and attending to) a single late-appearing item. Under both strategies, facilitation (in the form of reduced reaction times) would be observed when a subset of objects is cued. If only one of the items in the subset were attended, however, this facilitation would arise from the one-third probability that observers would correctly choose, on target-present trials, the single place holder marking the subsequent location of the target. Selective processing of a single cued item could explain a reaction time advantage for selective search. This hypothesis could not, however, account for a reaction time difference between feature search set and conjunction search set conditions, because there is no sense in which a single selected item could embody a feature set/conjunction set difference. Each single distractor (whether selected from a feature set or a conjunction set) shares one feature with the target; each target item possesses both the requisite features. The distinction between the feature search subset and conjunction search subset, therefore, only exists when more than one of the items is considered. As a result, a difference between these two conditions could only result if more than one of the indicated items were selected simultaneously for special processing.

To summarize, there are three critical ways in which the current experiment differs from previous research investigating the effects of abrupt onset (exogenous cuing) on the perception of features and conjunctions of features. First, this experiment uses multiple abrupt onsets to identify several objects in the display. Second, the effects of these multiple onsets are investigated in the context of other, uncued objects within the same display. Third, the distractors of the cued subset are manipulated to form either feature sets or conjunction sets. There are four independent variables manipulated in the experiment: cuing condition (cued, uncued); search set type (feature set, conjunction set); item numerosity (3 items, 15 items); and target condition (present, absent).

This experiment is designed to test the hypothesis that indexed items behave virtually as though they are the only items in the display. The following prediction arises from this hypothesis. Aside from a possible cost of filtering (cf. Treisman, Kahneman, & Burkell, 1983), search performance over abrupt onset items should show identical effects regardless of whether uncued items are also included in the display.

Method

Subjects. The data from eight subjects are reported for Experiment 1.[11] The subjects ranged in age from 22 to 36 years, and each had normal or corrected to normal vision. All subjects were familiar with the task, and each had a minimum of one full session of practice (data from these sessions are not reported). Subjects were paid $10.00 for each session of their participation in this experiment.

Apparatus and Stimuli. All experiments were conducted using a Zenith 386 computer, with a Hitachi monitor. Responses were collected by means of a computer mouse, using software designed to time-stamp each button press, and record the identity of the button pressed.

In each display, a number of objects occupied a subset of all possible display positions. The matrix of possible display positions can be described as three concentric hexagons, centred around fixation. Potential target positions include each of the vertices of the three hexagons (numbering 18), the midpoints of each edge of the middle hexagon (numbering 6), and two points on each edge of the outermost hexagon, placed so they divide the edge into three equal parts (numbering 12). Figure 2 shows the matrix of display positions.

From a viewing distance of 100 cm, each object subtended a visual angle of .7° (vertical) by .4° (horizontal). The minimum distance between contours of adjacent

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[11]One additional subject participated in the experiment. This subject, however, was eliminated from the analysis because her reaction times were extremely long (reaction times for this subject averaged 200 msec. longer than those for the remaining subjects; average reaction time in one condition was 2.5 standard deviations greater than the average for that condition).

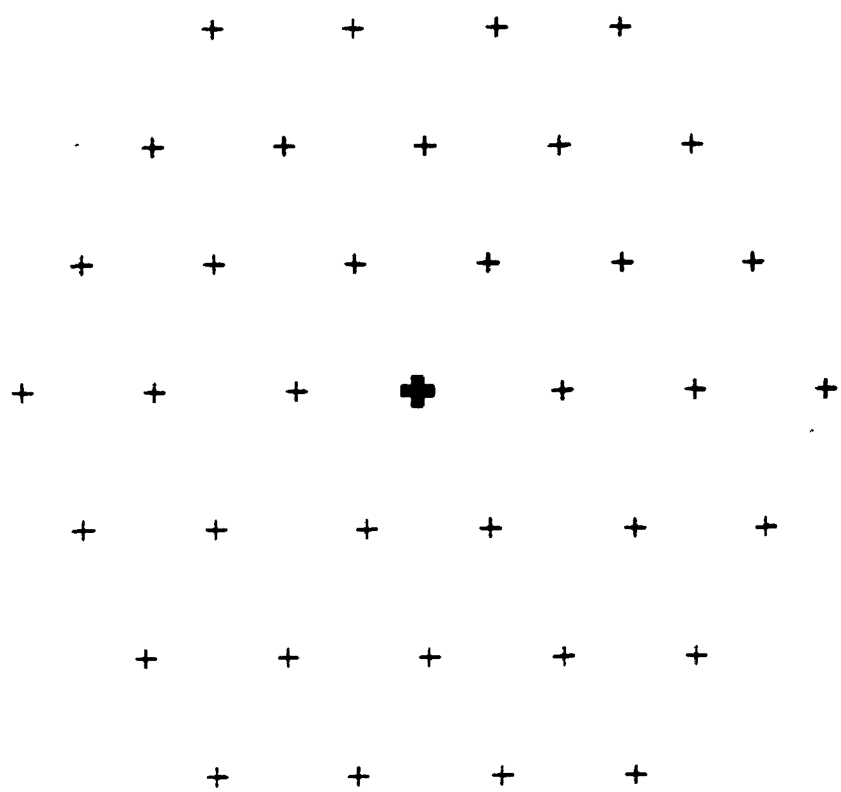

Figure 2. Matrix of display positions for Experiments 1, 3 and 3b.

objects was .92°. The maximum extent of the display was 10.4° (in the vertical direction) by 10.6° (in the horizontal direction). The maximum distance of a target object from fixation was 5.3°, and the minimum distance of a target object from fixation was .92°.

The factorial combination of cuing condition (cued, uncued), item numerosity (3 items, 15 items), search set type (feature set, conjunction set) and target condition (present, absent) resulted in 16 trial types. For cued trials, targets (if present) always appeared among the cued subset.

Each display included either three or fifteen objects. With a single exception, each of these items occupied a location randomly selected (without replacement) from a set of thirty-six predefined potential display locations (the matrix of potential display locations is described above). The single item with the pre-selected location was the target item on positive trials, and a distractor item on negative trials. Within each of the 16 trial types, all possible display positions occurred once as the pre-selected position (this has the effect of counterbalancing target position across conditions).

Displays with entirely homogenous distractors included three-item feature search displays (both 3-cue and 0-cue conditions), and fifteen-item, 0-cue feature search displays. The particular distractor used in these homogeneous displays was randomly selected from the two possible distractors.

All other displays (3-item conjunction search displays, both 3-cue and 0-cue, 15-item 0-cue conjunction search displays, and both types of 15-item 3-cue displays) included mixed distractors in approximately equal numbers[12] (for displays including targets, the number of distractors of each type was exactly equal; in no-target displays, the target was replaced with a distractor chosen randomly from the two possible types of distractors). The particular objects that were cued within the 15-item 3-cue displays were chosen to constitute either a feature search set (homogeneous distractors) or a conjunction search set (mixed distractors).

Procedure. Subjects were seated in a dimly-lit room, approximately 100 cm from the display screen. Each subject was instructed to search for a particular target (defined as a conjunction of colour and orientation) among a variable number of distractors, each of which shared one feature with the target. The particular target was determined randomly for each subject. Instructions to subjects included the information that targets were present on 50% of trials. Responses were collected using a computer mouse, with the mapping of response (yes/no) to button (left/right) randomly determined for each subject.

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[12]This experiment does not examine the effects of subset cuing in the context of homogeneous distractors. Therefore, there is no condition in which three cued items are displayed along with twelve uncued distractors of the same type. It was felt that the selection of a subset of items from among mixed distractors provided the strongest test of the hypothesis of selective processing of indexed items. If a feature/conjunction difference arises for subsets selected from identical larger set of mixed distractors (and hence identical conjunction displays), then the selected items are effectively determining, for the purposes of visual search, the 'type' of the display (feature or conjunction). When the subset is included among homogeneous uncued distractors, the 'type' of the subset (feature or conjunction) exactly determines the 'type' of the display (because homogeneous distractors included among homogeneous uncued items constitute a feature display, while heterogenous distractors included among homogeneous uncued items constitute a conjunction display). Under these conditions, a reaction time advantage for feature subsets would be predicted for processing of the display as a whole as well as for selective processing of the cued items.

General instructions included the injunction to "respond as quickly as possible, without making errors." Subjects were instructed to focus their eyes on the central fixation cross at the beginning at each trial, and they were encouraged to keep their eyes fixated throughout the trial. This proved particularly important in the fifteen-item cued trials, because eye movements between the onset of the cues and the change to the search display seemed to disrupt the information about which particular objects had been cued. Feedback was provided in the event of an error; subjects were instructed to slow their responses if they found they were making a large number of errors.

Specific instructions preceded the practice trials for each combination of cuing condition and item numerosity. At this time, subjects were told the number of items that would appear in each display; in addition, they were informed of the cuing condition for the upcoming trials. Trials were also blocked by search set type. This manipulation, however, was not explicitly described in instructions to the subject. In the case of the fifteen-item cued displays (the only displays in which the cuing reduced the number of potential target locations) subjects were informed that targets could only appear at the location of the cues, and they were further encouraged to use this information to help perform the search task quickly and accurately. Thus, subjects were instructed, in the cued condition, to restrict their search to the late-appearing items.

Within each of the eight types of target-present trials (two cuing conditions by two levels of item numerosity by two search set types), the target was placed once in each of the thirty-six potential display positions. An equal number of target-absent trials was created by replicating each target-present trial, with the target replaced by a distractor of the appropriate type. Thus, there were a total of 576 experimental trials (sixteen trial types, as described above, with 36 trials per type).

Trials were blocked by cuing condition, with the order of cuing condition determined randomly for each subject. Within each cuing condition, trials were blocked by item numerosity (the order of these two conditions was randomized for each subject), and within each combination of cuing condition and item numerosity, trials were blocked by search set type (again, the order was randomized). Target present and target absent trials were randomly intermixed within each block. Thus, there were eight blocks of trials in each experimental session, with 72 trials per block. Each of these blocks was preceded by thirty-six practice trials. Rest breaks were provided at the beginning of each block of trials.

Results

Errors were defined as an incorrect response: that is, a response of 'target present' if there was no target in the display, or a response of 'target absent' if a target was included in the display. The proportion of errors and the average reaction time was calculated for each subject in each of the sixteen combinations of cuing condition (0 cues, 3 cues), item numerosity (3 items, 15 items), search set type (feature, conjunction) and target condition (target present, target absent). Trials immediately following an error response were eliminated from the analyses, on the assumption that responses for these trials may be slowed as a direct result of the immediately preceding error response (Rabbitt, 1966). In addition, trials with reaction times greater than 2.5

standard deviations from the cell mean for each subject were discarded. Using both these criteria, the proportion of trials dropped from each combination of cuing condition, item numerosity, search set type and target condition ranged from 3.8% (for the 3 cue, 3 items, conjunction search target present trials) to 8.3% (for the 0 cues, conjunction search, target present trials including fifteen items). Descriptive statistics for both reaction time and errors (averaged over subjects) are presented in Table 1. Analysis of variance summary tables are presented in Appendix A.

A repeated measures analysis of variance, with independent variables of cuing condition (0 cues, 3 cues), search set type (feature set, conjunction set), item numerosity (3 items, 15 items), and target condition (present, absent), was conducted for the error data. Overall, subjects were quite accurate in their performance. Errors averaged 3.8% over all conditions. The analysis revealed a main effect of search set type ($F_{(1,7)}$=19.84, p<.01); observers make more errors for conjunction search sets (4.7%) than for feature search sets (3.[illegible]%). The main effect of item numerosity was also significant ($F_{(1,7)}$=21.6, p<.01), reflecting a greater proportion of errors for fifteen-item trials (4.4%) than for three-item trials (3.2%). There is also a tendency to commit more false negative errors (that is, to miss a target) than false positive errors (that is, to incorrectly indicate that a target is present), as indicated by the main effect of target condition ($F_{(1,7)}$=8.75, p<.05; error rates of 2.6% for target absent trials, and 5.0% for target present trials). Finally, there is a significant interaction of item numerosity and target condition ($F_{(1,7)}$=6.10, p<.05). None of the pairwise contrasts within this interaction is significant (for Tukey's HSD, critical $q_{(.05,4,14)}$=4.11; largest obtained q is

Table 1
Experiment 1: Descriptive Statistics

Condition				Reaction Time (msec)	s.d.	Errors (%)	s.d.
No. of Cues	No. of Items	Search Set Type	Target Presence				
0	3	feature	absent	531	46	1.1	2.2
			present	508	42	3.0	5.3
		conjunction	absent	617	84	3.0	2.3
			present	591	49	4.1	4.5
	15	feature	absent	580	61	2.3	4.2
			present	555	63	3.4	2.5
		conjunction	absent	810	143	2.3	3.5
			present	723	87	8.3	5.0
3	3	feature	absent	527	55	1.5	2.3
			present	527	59	3.4	3.7
		conjunction	absent	572	48	4.5	3.6
			present	564	63	5.3	5.0
	15	feature	absent	589	90	3.4	4.1
			present	562	73	6.0	4.6
		conjunction	absent	644	60	3.0	3.6
			present	576	71	6.9	4.6

3.99, for the feature versus conjunction comparison within 15-item displays). The interaction, however, appears to reflect particularly error-prone performance for the 15-item conjunction search displays (error rate for this condition of 6.1%, compared to 2.7% for 15-item feature search displays, 3.9% for 3-item conjunction search displays and 2.5% for 3-item feature search displays).

Reaction time data were examined using a repeated measures analysis of variance with cuing condition (0 cues, 3 cues), search set type (feature set, conjunction set), item numerosity (3 items, 15 items), and target condition (present, absent) as independent variables. The analysis revealed a significant three-way interaction of search set type, cuing condition and item numerosity ($F_{(1,7)}$=8.39, p<.05). This interaction was explored using tests of simple two-way interactions, along with specific pairwise contrasts.

The first set of simple-two way interactions examines the effects of search set type and item numerosity separately for the 0 cue and the 3 cue conditions (see Figures 3 and 4 for depictions of the simple two-way interactions for the 0 cue and 3 cue conditions respectively).

Within the 0 cue condition, there is a main effect of item numerosity ($F_{(1,7)}$=22.27, p<.01), a main effect of search set type ($F_{(1,7)}$=31.46, p<.01), and a significant interaction of these two factors ($F_{(1,7)}$=6.81, p<.05). The main effects of item numerosity and search set type reveal that reaction times are longer for the fifteen-item, as opposed to 3-item, trials (average reaction times of 667 msec and 562 msec respectively for 15 item and 3 item trials), and subjects are slower to respond to

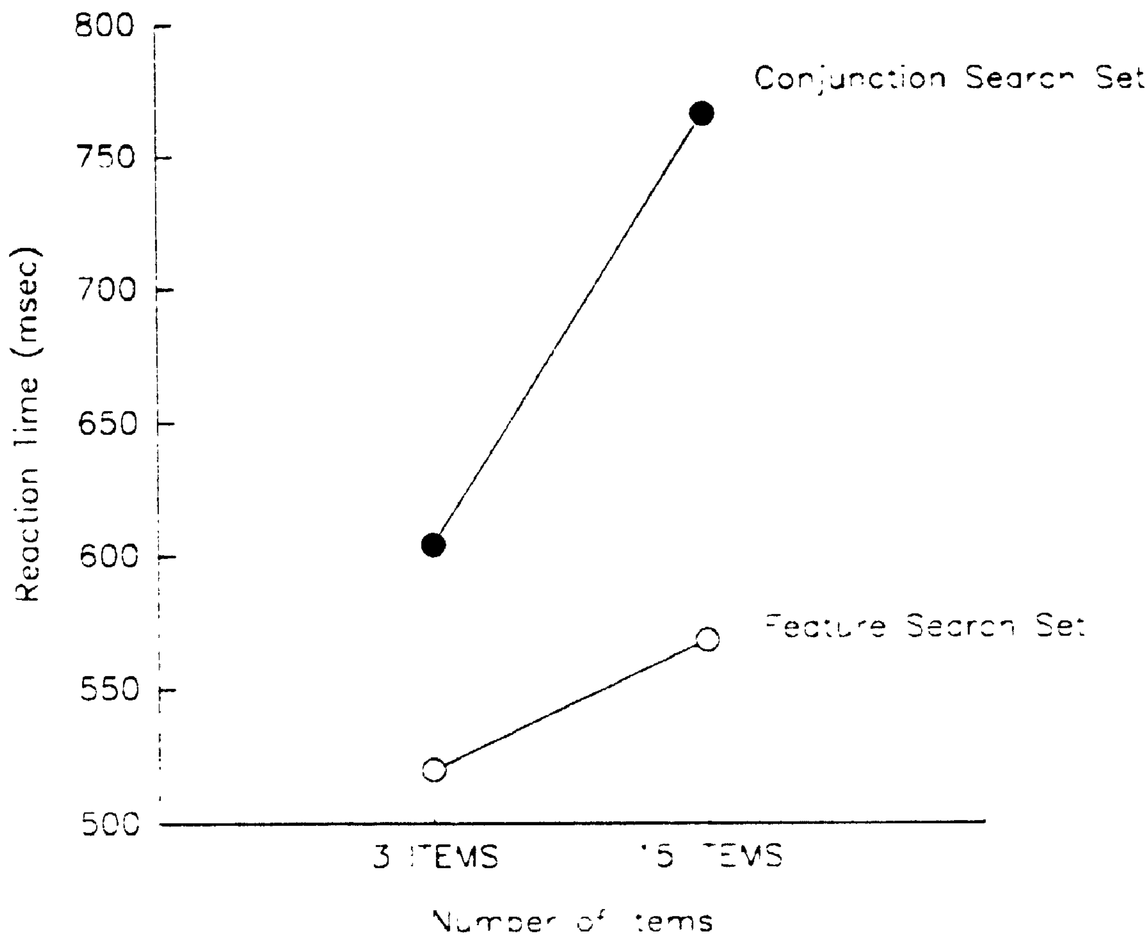

Figure 3. Experiment 1: Simple two-way interaction for 0 cue trials of item numerosity and search set type.

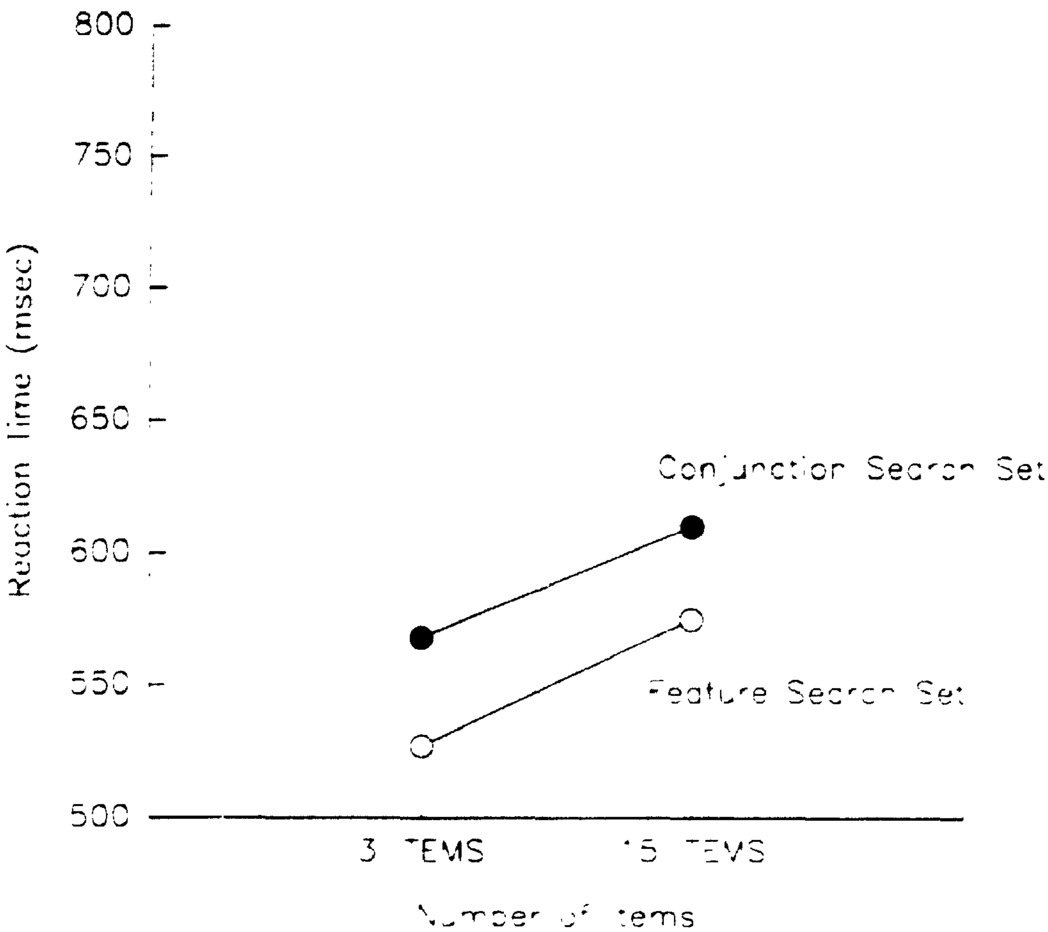

Figure 4. Experiment 1: Simple two-way interaction for 3 cue trials of item numerosity and search set type.

conjunction search sets than to feature search sets (average reaction times of 685 msec and 544 msec respectively for conjunction search sets and feature search sets). The interaction is due to the greater effect of item numerosity for conjunction search sets as opposed to feature search sets. The 162 msec effect of item numerosity for conjunction search sets (average reaction times of 766 msec for 15-item displays and 604 msec for 3-item displays) is significant by Tukey's HSD (critical $q_{(.05;4,14)}$=4.11, observed q of 7.32). In contrast, the 48 msec effect of item numerosity for feature search sets (average reaction times of 568 msec for 15-item displays and 520 msec for 3-item displays) does not reach significance (observed q of 2.17). As expected, this pattern of reaction times matches that typically observed in visual search. In particular, an increase in the number of items in the display tends to have little effect on reaction time for feature search sets, which include homogenous distractors. In contrast, adding more items to a conjunction search display (including heterogenous distractors) tends to significantly increase reaction time.

Within the 3 cue condition, there is a significant effect of item numerosity ($F_{(1,7)}$=32.55, p<.01), and a significant effect of search set type ($F_{(1,7)}$=20.12, p<.01). The interaction of the two factors is not significant in this analysis ($F_{(1,7)}$=.47, *n.s.*). The main effect of item numerosity reflects slower responses in the fifteen-item condition (average reaction times of 593 msec for 15 item displays and 548 msec for 3 item displays), while the main effect of search set type reflects slower responses for conjunction search sets (average reaction times of 589 msec for conjunction search sets and 551 msec for feature search sets). When three display items are cued, the addition of uncued distractors results in an overall increase in reaction time (a main effect of item numerosity). This overall slowing of response is, however, the only effect of the added distractors. In particular, the addition of mixed (but uncued) distractors to the display does not eliminate the feature search set advantage. There is no interaction of search set type and item numerosity, indicating that the effect of search set type is consistent across three items alone and three items selected from among fifteen.

It is also informative to examine the simple two-way interactions separately for the feature search trials and for the conjunction search trials. Within the conjunction search trials, the main effects of cuing condition and item numerosity are both significant ($F_{(1,7)}$=15.28, p<.01, for cuing condition, and $F_{(1,7)}$=26.18, p<.01, for item numerosity), as is the interaction between these two factors ($F_{(1,7)}$=6.71, p<.05). Examination of this interaction (presented in Figure 5) reveals a larger effect of cuing condition for the fifteen item displays than for three items displays. For fifteen-item displays, there is a significant cuing advantage (average reaction times of 766 msec and 610 msec for the 0 cue and 3 cue conditions respectively; Tukey's HSD requires a critical $q_{(.05;4,14)}$=4.11, and observed q=6.53). For three-item displays, however, the cuing advantage is not significant (average reaction times of 604 msec and 568 msec for the 0 cue and 3 cue conditions respectively; observed q=1.51). Thus, in 15-item displays including mixed distractors, cuing a subset of items results in faster search performance.

In contrast, the analysis of the simple two-way interaction for feature search displays (presented in Figure 6) reveals a significant main effect of item numerosity

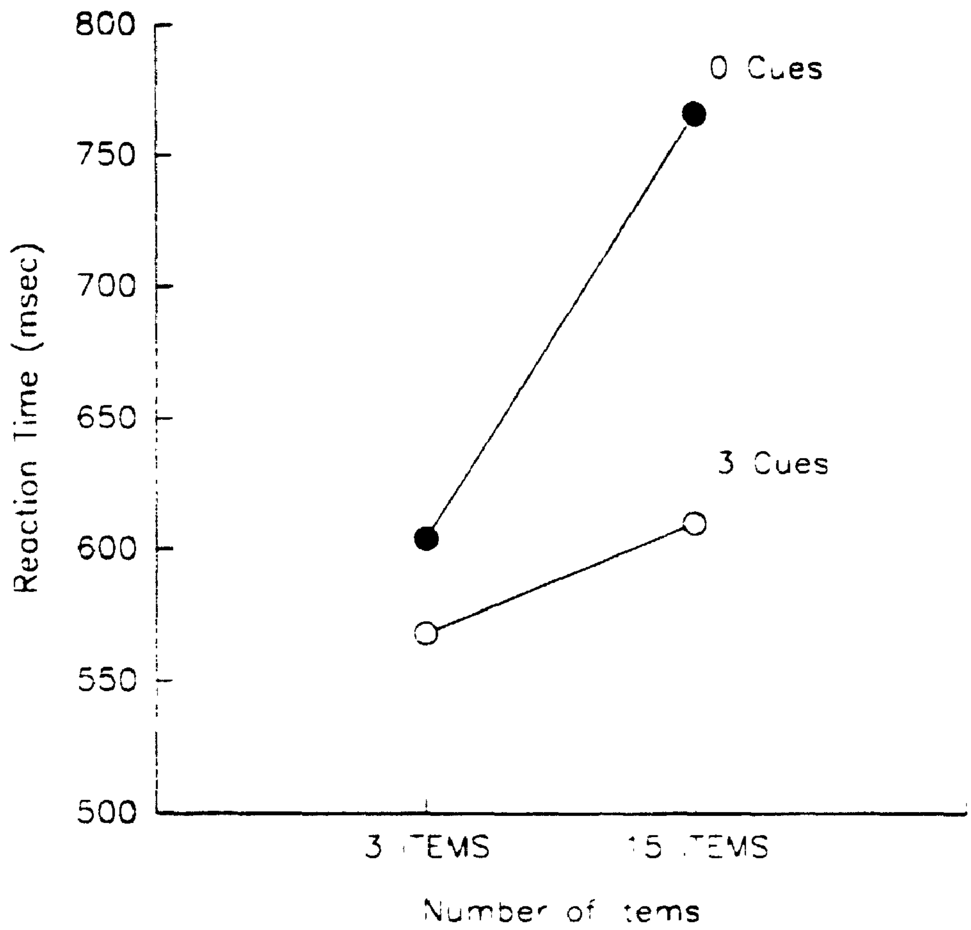

Figure 5. **Experiment 1: Simple two-way interaction for conjunction search set trials of item numerosity and cuing condition.**

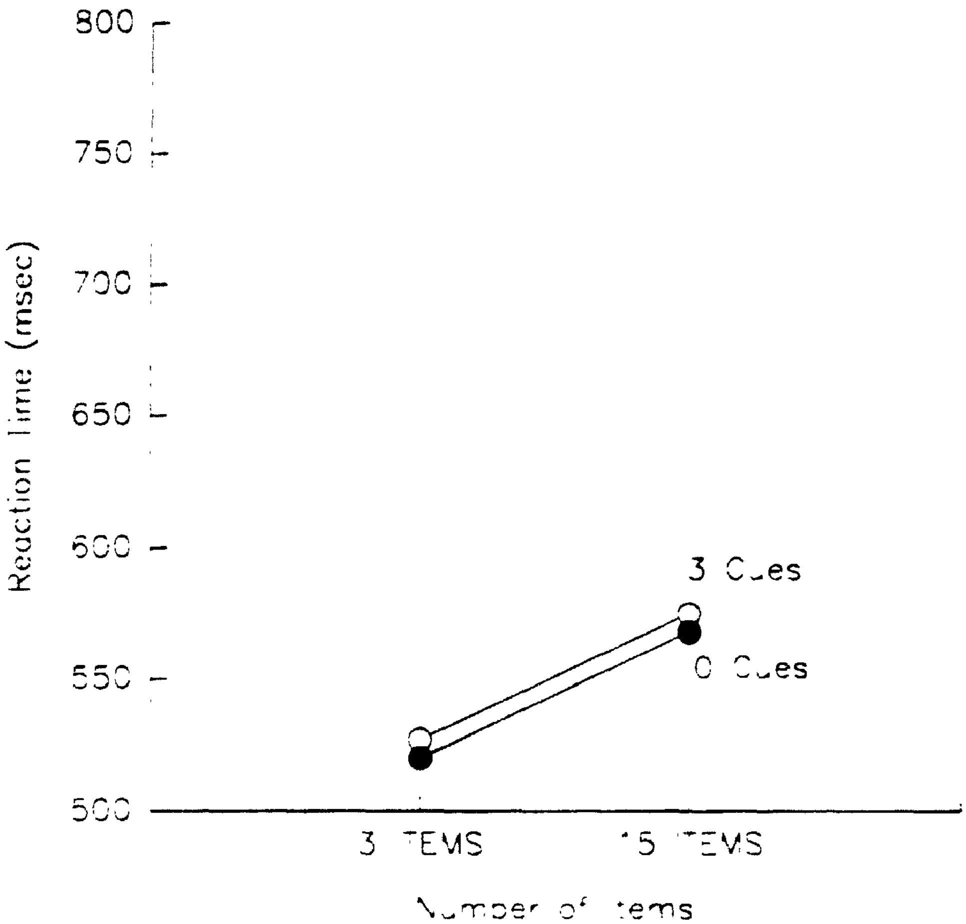

Figure 6. Experiment 1: Simple two-way interaction for feature search set trials of item numerosity and cuing condition.

($F_{(1,7)}$=39.77, p<.01). Overall, subjects are faster to respond to three-item feature search displays (average reaction time of 524 msec for 3-item displays, and 572 msec for 15-item displays). There is, however, no general reaction time advantage for the cued, as opposed to uncued, condition (main effect of cuing condition, $F_{(1,7)}$=.38, *n.s.*), and no evidence of a cuing advantage that is specific to the fifteen-item displays ($F_{(1,7)}$=.00, *n.s.* for the interaction of cuing condition and item numerosity). It is perhaps surprising that there is no cuing effect for the feature search subset fifteen-item displays. In the 0-cue condition, the display includes fifteen identical distractors (or 14 distractors and one target item). In contrast, displays in the fifteen-item three-cue condition include mixed distractors (either 8 of one type and 7 of the other, or 7 of each type plus one target). In this condition, a subset of three items including homogenous distractors are cued, and observers are instructed to restrict their search to this cued subset. It appears that observers are very successful in following this instruction. Given appropriate cuing, the change from twelve homogenous distractors (in the fifteen-item 0 cue condition) to twelve mixed distractors (in the fifteen-item 3 cue condition) does not slow search performance. In general, search among conjunction displays (with mixed distractors) is much slower than search among feature displays (with homogenous distractors); the cuing procedure completely eliminates this expected difference in reaction time.

Discussion

The significant feature search advantage for cued displays, observed in the results of Experiment 1, strongly suggests that observers are placing indexes on all three (or at least two) of the late-onset items. If only one item among the three were being selected as the focus of a unitary attentional process, it would be difficult to account for a difference in performance between the feature search subset and conjunction search subset conditions. This is because the difference between these two conditions is defined across the set of items. The distinction between feature subsets and conjunction subsets does not exist for a single item. It appears, therefore, that at least two (and most likely all three) of the late-onset items receive selective processing.

Most theories of visual search (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe et al., 1989) attribute the feature search advantage to a parallel process that operates over the entire display. In the current experiment, the same advantage is observed for a feature subset selected from a larger display including mixed distractors. If the feature set advantage observed here is attributed to a parallel mechanism similar to that proposed in existing search theories, then it must be the case that this parallel process is applied selectively over the indexed items. Alternatively, it is always possible to conceive of some serial mechanism that would result in a feature set advantage. For example, one possibility is a template matching process that checks each indexed item in turn against a representation of the target item. There is at least one assumption under which this sort of process might reach completion faster for the feature search subsets. If the comparison is faster when the item to be compared on step n is identical to that compared on step n-1, the set of comparisons would be finished earlier for feature search subsets.

These results suggest that a number of spatially disparate indexed items are treated virtually as if they are the only items in the display. Search is speeded when a subset of items is selected from a larger conjunction search display. Furthermore, search over a feature subset selected from a larger conjunction search display acts more like a *feature* search than a *conjunction* search, despite the fact that the larger display in fact includes mixed distractors. There is a (not unexpected) cost of filtering the FINSTed items from among uncued distractors (see Treisman, Kahneman & Burkell, 1983); search over late-appearing (cued) items is slower within fifteen-item displays than within three-item displays. Aside from this difference, search over three items selected from among fifteen proceeds exactly as if the three items appeared alone. In particular, the feature search advantage observed in the three-item displays is replicated when three items are selected from among fifteen.

Thus, it appears that observers are able to simultaneously index a number of spatially disparate objects in a visual display, and subsequently process those objects virtually as if they were the only items that appear. This result argues for a model in which visual indexes mark items for later attentional processing; in other words, this evidence supports the FINST hypothesis.

Experiment 2: Effect of Dispersion of Indexed Items

The results of Experiment 1 suggest that observers can simultaneously select a subset of display items, and subsequently perform a search for a conjunction target that is restricted to the selected items. This result argues for a FINST-like model of visual indexing, in which each of a number of spatially distinct objects can be simultaneously marked for subsequent processing, and thereafter treated (in some senses) as if they are the only items in the display. A further assumption of the FINST model is that indexed objects can be accessed in a time that is independent of their distance, either from each other, or from the current focus of processing. This is because, under FINST theory, an indexed object can be accessed directly, without the need for a "visual scan", by following the index.

Most current attentional theories (e.g., 'spotlight' theory; LaBerge, 1983; Posner et al., 1980; or 'zoom lens' theory; Eriksen & St. James, 1986; Eriksen & Webb, 1989; Eriksen & Yeh, 1985) predict that search performance should decline (i.e., reaction time should increase) as the distance between the items increases (e.g., Castiello & Umiltà, 1990; Egeth, 1977; Eriksen & St. James, 1986; Henderson, 1991; LaBerge, 1983; LaBerge & Brown, 1989; Posner et al., 1980). Within these theories, the decrease is explained in one of two ways. Under a model of a unitary attentional field that has, at any given time, a single object as its focus, the increased reaction time with increased distance between objects is explained by the analog movement of the unitary attentional beam. If attention is moved by scanning across the display, greater time should be required to move a longer distance. Thus, more disparate sets of cued items would be processed more slowly. Alternatively, the zoom lens model might suggest that the unitary attentional beam expands and contracts as needed to cover the entire set of cued locations. Under this assumption, the fixed attentional resources are distributed over a greater area as the distance between the cued objects (and thus the size of the required attentional beam) increases. Given that the time required for visual processing is related to the attentional resources allocated to the particular area to be processed, it will take longer to process the cued items when they (and thus the unitary attentional field) are spread over a greater region of the display.

In contrast, the FINST theory assumes that individual markers are placed on each of the FINSTed items, and that these markers facilitate immediate access to the items. Therefore, the FINST theory predicts that the time required to access the marked items will be independent of their particular spatial locations, and independent of the degree of dispersion of the set of marked items. In particular, FINST theory predicts that reaction time will not increase with the degree of dispersion, in direct contrast to the prediction of spotlight and zoom lens theories of attention.

Experiment 2 offers an explicit test of the hypothesis that the time required to process a set of items will not increase with the dispersion of the items. Three conditions are manipulated in the experiment: dispersion (the levels of this variable are explained in method section); search set type (feature search set, conjunction search set); and target condition (target present, target absent).

Method

In many respects, the procedure for Experiment 2 was identical to that for Experiment 1. Exceptions are explicitly noted in this section.

Subjects. Eight University of Western Ontario students were paid to participate in a 45-minute session. All subjects had normal or corrected-to-normal vision. Subjects were experienced in the cued search task; each had participated in at least one previous cued search experiment.

Stimuli. Each display in Experiment 2 included a total of twelve items, evenly spaced on the circumference of a circle centered at fixation. Subjects were encouraged to fixate the center of the display. In pilot experiments, the combination of fixation maintained at the center of the display and a consistent set of display locations led to some adaptation and afterimage. Therefore, in order to combat this fading, the display positions were perturbed a small amount between trials by alternating between two sets of positions. Within each set of positions, the items were equally spaced on the circumference of a circle centered at fixation; the radius of one circle was slightly smaller than the other (2.9° versus 3.4°).

From a viewing distance of 100 cm, each object subtended .7°. Each of the twelve objects was 2.9° from fixation at the small radius, and 3.4° from fixation at the large radius. The distance between nearest contours of adjacent objects was .9° for the smaller radius and 1.1° for the larger radius.

The spatial dispersion of the members of the cued subset was manipulated in this experiment. In every case, each of the two outer items in the cued subset was equally distant from the central item in the set. Dispersion was manipulated by changing the number of uncued locations (and thus objects, since all display locations are occupied on every trial) interspersed between the central cued location and the two outer cued locations. This number could be 0 (no intervening items), 1 (one uncued item between each outer cued item and the central cued item), 2 (two uncued items between each outer cued item and the central cued item) or 3 (three uncued items between each outer cued item and the central cued item. Within the text, these four levels of dispersion are referred to as 0, 1, 2 and 3. The distance (center to center) between each outer item and the central cued item was 1.1° for the small radius (2.0° large radius) for dispersion 0, 3.1° for the small radius (3.7° large radius) for a dispersion 1, 4.5° for the small radius (5.4° large radius) for a dispersion 2, and 5.7° for the small radius (6.3° large radius) for a dispersion 3. See Figure 7 for a diagram of one of the two sets of display positions (the second set of positions is identical, except for a small change in overall radius of the circle).

As dispersion increases, the size of the region including all cued items also increases. For dispersion 0 the entire set is confined to one quadrant of the display; for dispersion 1, the set is confined to one third of the display; for dispersion 2 the set is confined to one half of the display; and for dispersion 3 the set of items is evenly dispersed throughout the entire display.

Procedure. Each search display included 6 distractors of one type, and either six distractors of the other type, or five distractors and a target. In every trial, three

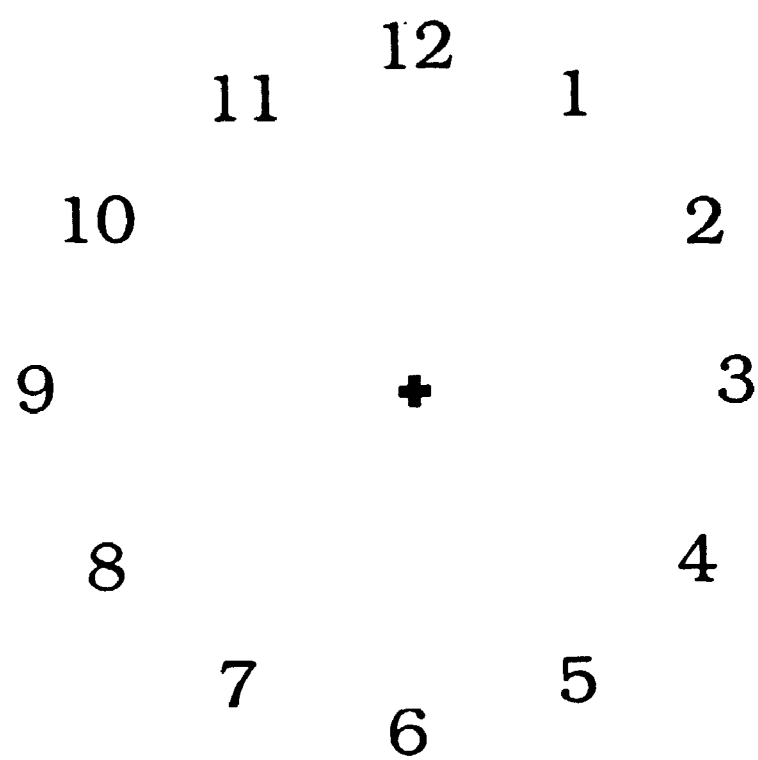

Figure 7. Matrix of display positions for Experiments 2 and 2b. The following are examples of sets of cued locations for each of the levels of dispersion:

dispersion=0 locations 12, 1 and 2
dispersion=1 locations 11, 1 and 3
dispersion=2 locations 10, 1 and 4
dispersion=3 locations 9, 1 and 5

The target appears equally often in the center of the group (position 1), clockwise of center (e.g., position 2 at dispersion 0), and counterclockwise of center (e.g., position 12 at dispersion 0).

of the twelve objects were cued by the late onset procedure used in Experiment 1; the target, if present, was always among this cued subset.

Six of the twelve display positions were designated as target positions.[13] These included every second display position. Within each combination of dispersion and search set type, targets appeared equally often at each potential target location. In addition, the position of the target within the cued subset was counterbalanced, with the target occupying the central, left, and right locations in the cued subset an equal number of times, resulting in 18 trials within each combination of dispersion and search set type (see Figure 7 for examples of sets of cued positions). For target-absent trials, the target was replaced by a distractor, chosen so that the number of distractors of each type was equal. The total number of experimental trials was 288.

Trials were blocked by search set type (feature search set, conjunction search set). Target-present and target absent trials were randomly intermixed in each block, as were the various levels of the manipulation of dispersion. Thirty-six practice trials preceded each of the feature search set and conjunction search set blocks. Subjects were given the opportunity for a rest break every 72 trials.

Instructions were given at the beginning of the experiment. As in Experiment 1, subjects were instructed to search for a target defined as a particular combination of colour and orientation. Neither the manipulation of search set type nor the dispersion manipulation were described to the subjects.

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[13]The choice to restrict targets to six of the twelve display positions was purely pragmatic. A complete counterbalancing of all relevant factors over twelve positions would result in too many trials to be completed in one experimental session.

Results

Average reaction time and proportion of errors were calculated for every combination of dispersion (0, 1, 2, 3), search set type (feature set, conjunction set) and target condition (target present, target absent). Errors are defined either as a response of 'target present' when there was no target in the display, or a response of 'target absent' when the display included a target item. As in Experiment 1, trials immediately following an error response were removed from the calculation, as were trials with a correct reaction time more than 2.5 standard deviations from the cell mean. These criteria resulted in the elimination of between 2.1% (for dispersion 1, feature search set, target present trials) and 8.3% (for dispersion 2, conjunction search set, target present trials) of the trials in each cell. Error rate descriptive statistics are presented in Table 2, and reaction time descriptive statistics are presented in Table 3. Summary tables for analyses of variance are presented in Appendix B.

The effects on error rates of target condition (present, absent), search set type (feature set, conjunction set) and dispersion (0, 1, 2, 3) were evaluated in a repeated measures analysis of variance. There were two significant effects in the error analysis: the main effect of search set type ($F_{(1,7)}$=7.68, p<.05), and the interaction of target condition by search set type ($F_{(1,7)}$=11.91, p<.05). The main effect of search set type reflects the fact that subjects make significantly more errors in the conjunction search set condition (5% errors for conjunction search sets, 2.6% errors for feature search sets). Within the significant interaction, error rates for conjunction subsets were 5.9% and 4.1% for target absent and target present trials respectively; for feature search sets,

Table 2
Experiment 2: Percent Error Descriptive Statistics

Dispersion	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*
0	2.3	*3.1*	3.8	*3.1*	9.9	*3.8*	3.5	*7.8*
1	1.5	*2.8*	3.6	*4.2*	3.6	*4.2*	4.3	*7.7*
2	.8	*2.1*	4.3	*4.9*	6.5	*5.6*	5.0	*4.6*
3	.8	*2.1*	3.6	*4.2*	3.6	*4.2*	3.5	*5.0*

Table 3
Experiment 2: Reaction Time Descriptive Statistics

Dispersion	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*
0	574	*55*	532	*50*	643	*37*	573	*50*
1	614	*130*	593	*72*	655	*55*	587	*41*
2	591	*58*	575	*75*	641	*70*	586	*81*
3	570	*68*	562	*53*	623	*66*	587	*69*

the error rates were 1.4% and 3.8% for target absent and target present trials. Tests of means using Tukey's HSD (critical $q_{(.05;4,14)}$=4.11) revealed that none of the pairwise differences were significant (largest obtained q is 2.96, for the comparison of target-absent feature search set and conjunction search set error rates).

Reaction time data from eight subjects were analyzed in a repeated measures ANOVA with target condition (present/absent), search set type (feature set/ conjunction set) and dispersion (0, 1, 2 or 3) as factors. The analysis revealed a main effect of target condition ($F_{(1,7)}$=14.00, p<.05), a main effect of search set type ($F_{(1,7)}$=14.27, p<.01), and an interaction of these two factors ($F_{(1,7)}$=6.32, p<.05; see Figure 8). These main effects reflect the following differences. The significant main effects can be interpreted as follows. Reaction times are significantly faster for target present, as opposed to target absent, trials (average reaction times of 575 msec and 614 msec respectively), and significantly faster when the search set is a feature type, as opposed to conjunction type (average reaction times of 577 msec and 612 msec respectively). Although none of the pairwise differences in the interaction were significant by Tukey's HSD (critical $q_{(.05,4,14)}$=4.11, largest obtained q is 3.48, for the comparison of target-absent and target-present reaction times for conjunction search subsets), it appears that the significant interaction reflects the larger difference between target present and target absent trials for conjunction search sets (target present, 583 msec; target absent, 641 msec), than for feature subsets (target present, 560 msec; target absent, 587 msec).

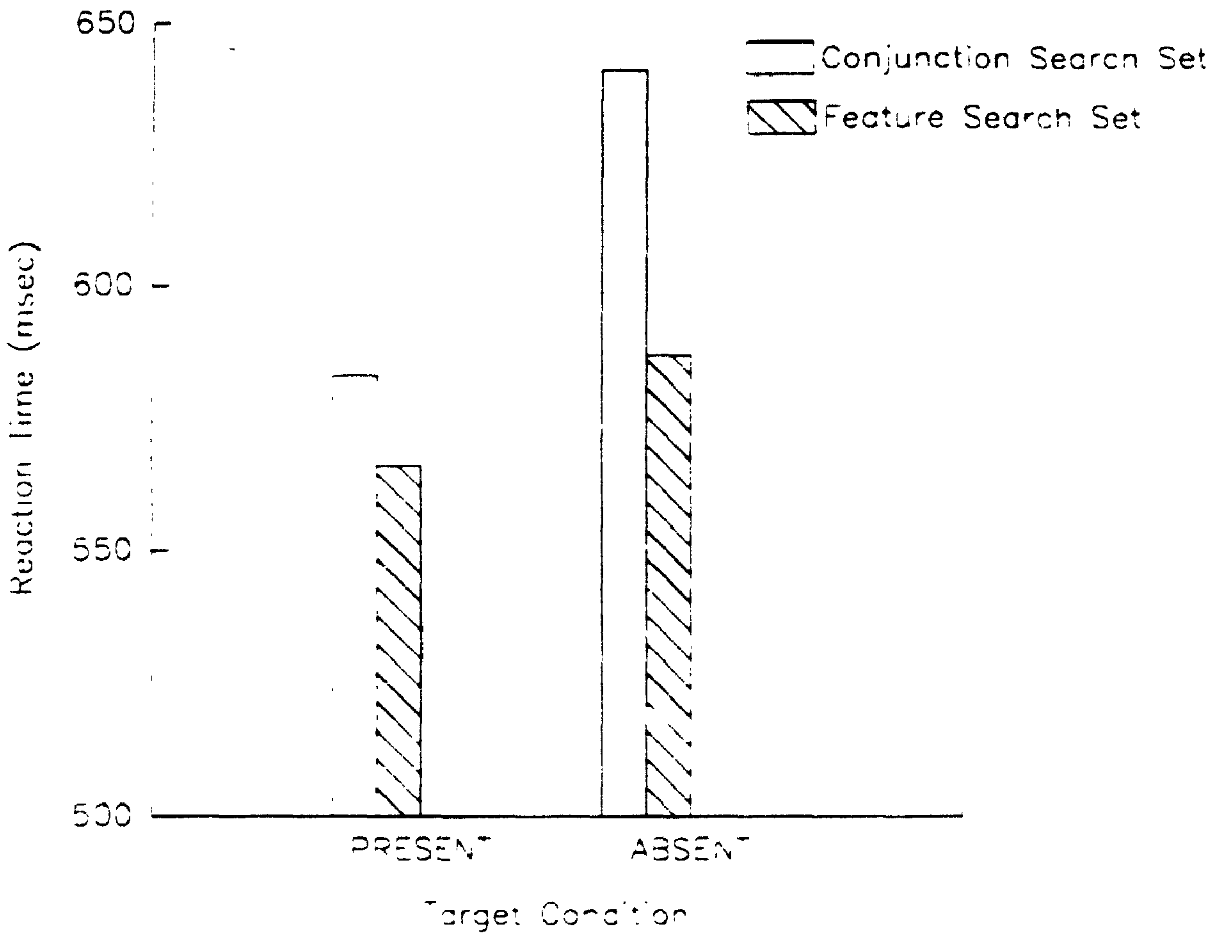

Figure 8. Experiment 2: Interaction of target condition and search set type.

In addition to these predicted effects, the analysis revealed an unpredicted main effect of dispersion ($F_{(1,7)}$=4.56, p<.05; see Figure 9). Inspection of the mean reaction times for each level of dispersion, however, reveal that this effect does not represent the systematic increase in reaction time as dispersion of the items increases that would be predicted by traditional attentional theories (observed mean reaction times were: dispersion 0, 581 msec; dispersion 1, 612 msec; dispersion 2, 598 msec; dispersion 3, 586 msec). None of the pairwise comparisons was significant by Tukey's HSD (critical $q_{(.05;4,7)}$=4.68, largest obtained value, for the difference between the smallest dispersion (0) and the next level of dispersion (1) q=2.33), making interpretation of the effect of dispersion somewhat difficult. Nonetheless, it appears that reaction times are particularly fast when the cued objects occupy adjacent locations (when dispersion=0). In addition, reaction times tend to *decrease* as the number of intervening locations (and objects) increases from one to three (changes in the level of dispersion from 1 to 3).

The main effect of dispersion remained marginally significant when trials in which the members of the cued subset occupy adjacent positions (when dispersion=0) were eliminated from the analysis ($F_{(1,7)}$=4.46, .05<p<.1, evaluated by the conservative F test to correct for violation of sphericity, as suggested by Kirk, 1982). This suggests that the effect of dispersion should not be attributed solely to fast reaction times when the three items occupy adjacent locations.

To investigate further the unexpected main effect of dispersion, reaction time analyses were conducted for each individual subject. The independent variables in each analysis of variance included target condition (target present, target absent),

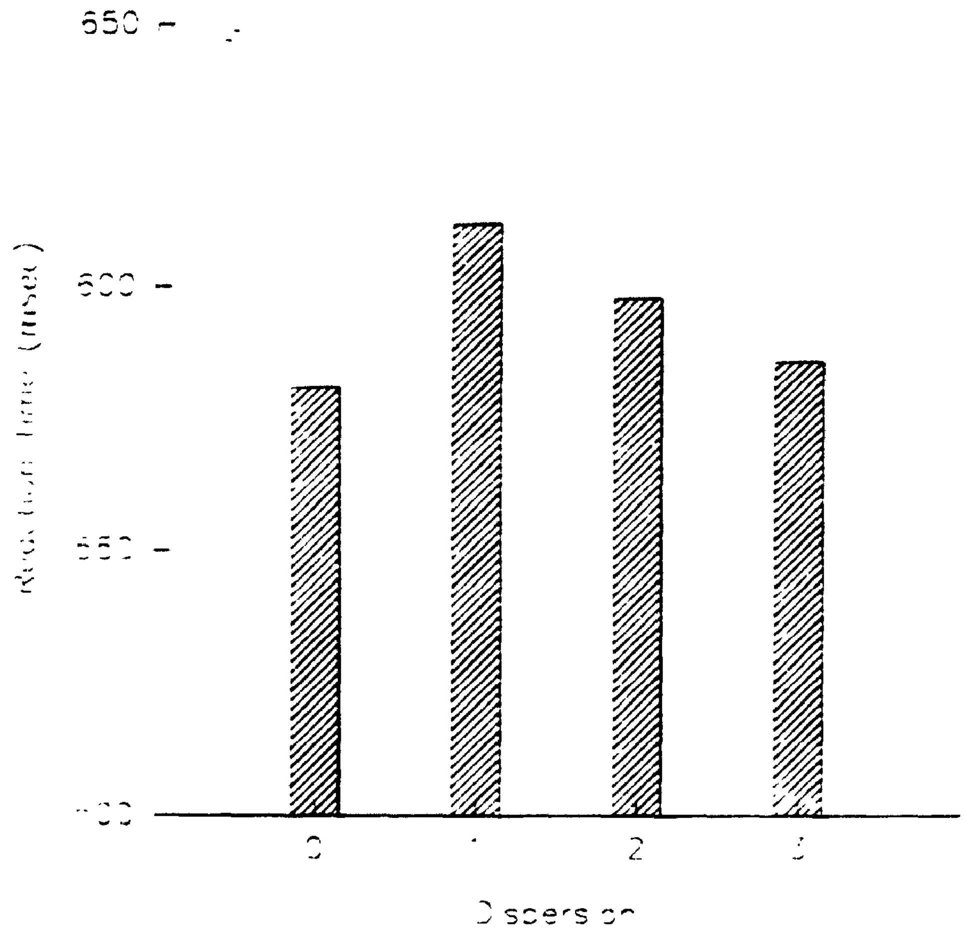

Figure 9. **Experiment 2: Main effect of dispersion.**

search set type (feature set, conjunction set) and dispersion (0, 1, 2, 3). Table 4 indicates the significant effects for each of the eight subjects who participated in the experiment (analysis of variance tables for individual subjects are included in Appendix B). The effect of dispersion is significant in four of the eight individual subject analyses (Figure 10 presents the means across dispersion for the four subjects with significant effects, and Figure 11 presents the same information for those subjects who did not show a significant effect of dispersion). In three of the four cases of a significant effect of dispersion, the pattern of reaction time over dispersion is identical: short reaction times are observed at the smallest level of dispersion (0) and the longest reaction times at the next level of dispersion (1), with reaction time steadily decreasing as dispersion increases from level 1 to level 3.[14] For three of the four subjects, the reaction times are significantly faster for a dispersion of 0 than for a dispersion of 1 (by Tukey-Kramer Modification of the HSD test; Kirk, 1982). For two of the four subjects, the effect of dispersion remains significant when trials with a dispersion of 0 are removed from the analysis (this effect is marginal, $.05<p<.1$, for a third subject).

Discussion

Experiment 2 replicates the basic finding of Experiment 1. Searches for conjunction targets are faster among feature search subsets than among conjunction search subsets. This replication strengthens the interpretation that indexed subsets are

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[14]As evident in Figure 11, a similar pattern of reaction time over distance is also observed for two of the four subjects who did not exhibit a significant distance effect.

Table 4
Experiment 2: Significant Effects for Individual Subject Reaction Time Analyses

	Subject							
	CR	PP	BA	JB	JG	RE	BF	MH
Main Effects								
Target Presence(P)		**	**			*	**	**
Search Set Type(T)	**		**	**		*	**	*
Dispersion(D)					**	*	*	*
2-Way Interactions								
P×T			**	**				
P×D								
T×D								
3-Way Interactions								
P×T×D								

* $p<.05$
** $p<.001$

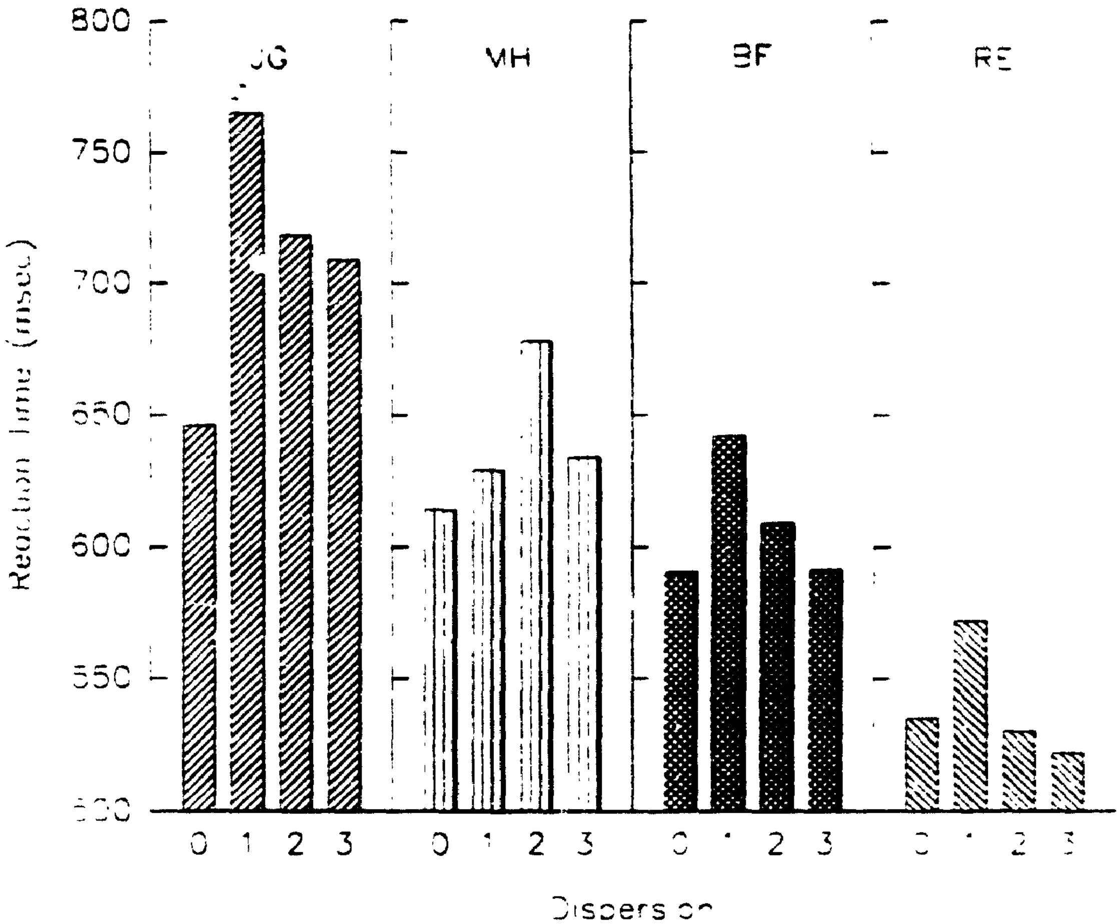

Figure 10. **Experiment 2: Dispersion effect for individual subjects, significant effects only.**

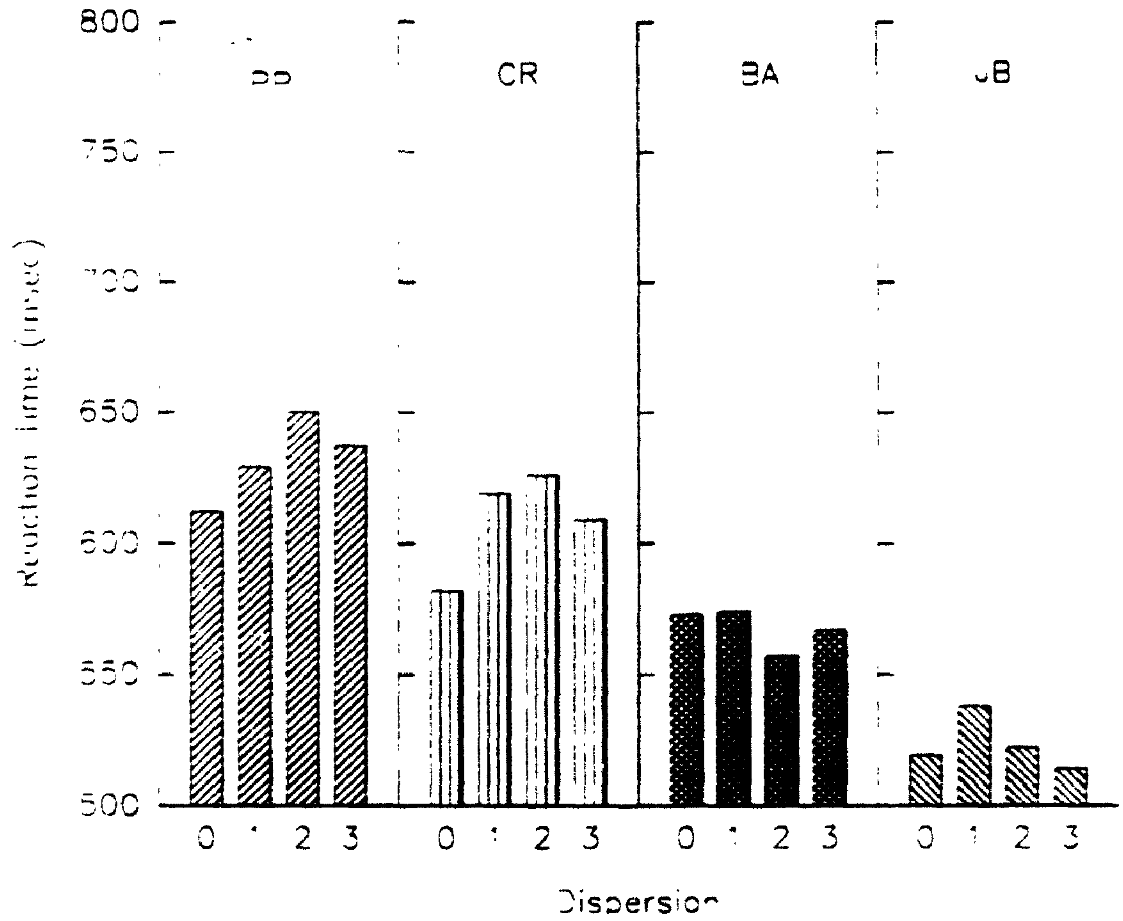

Figure 11. **Experiment 2: Dispersion effect for individual subjects, non-significant effects only.**

treated as if they are the only items in the display. Once again, there is evidence that feature information across the set of FINSTed items is registered by a fast process, while conjunction information is obtained by a slower process.

In Experiment 2, there is also a significant interaction of target presence and search set type. Examination of the reaction times involved in the interaction suggests that particularly long reaction times in the target absent, conjunction search set condition may be responsible for the interaction as well as the main effects of search set type and target condition. One interpretation of this effect is that (for reasons explicated in the results section) observers are using a strategy of item-by-item serial processing to confirm their response in this condition. Alternatively, the relatively large difference between target present and target absent reaction times in the conjunction subset condition could also be predicted by a model of parallel search among feature subsets and serial search among conjunction subsets. The current experiment does not support discrimination between these two possibilities.

The significant effect of dispersion is an unexpected finding. There appear to be two aspects to this dispersion effect: 1) fast reaction times are observed when the members of the cued subset occupy adjacent locations in the stimulus array; 2) a steady decrease in reaction time as dispersion increases with an increase in the number of intervening items from one to three. It is likely that the two aspects of the dispersion effect arise from different factors.

The speeding of responses at the smallest dispersion (where there are no intervening objects) may be explained by facilitation due to eye movements. Prior to their abrupt onset, the locations which the cued subset will occupy are marked by spaces in the stimulus array. The interval of one second between the onset of the early-appearing objects and the onset of the cued subset allows time for observers to move their eyes to the region that will be occupied by the abrupt onset items. When the three objects occupy adjacent locations, an eye movement to the location of one of the late onset objects would bring all three cued objects close to the new point of fixation. The proximity of all three objects to fixation would result in speeded processing for all members of the cued subset. When the objects do not occupy contiguous locations, an eye movement will result in the foveation of only one of the three cued locations; thus, it is unlikely that eye movements would benefit the processing of all three objects. Note that the eye movement explanation does not rest on the assumption that eye movements are restricted to trials in which the cued objects occupy adjacent locations. Instead, it is assumed that eye movements will facilitate processing of *all* of the cued subset when the three items occupy adjacent locations, but only *one* of the items of the cued subset when they occupy distant locations.

Eye movements could not, however, account for the remainder of the dispersion effect. There is a consistent reduction of reaction time as dispersion (along with the number of items intervening between cued items, and the distance between cued items) increases. This reduction in reaction time is unlikely to be due to chance, because the main effect of dispersion remains marginally significant when trials in which the indexed items occupy adjacent locations are removed from the analysis. Furthermore, individual subject analyses reveal that, of the four subjects who demonstrate a significant effect of dispersion, two subjects show a significant decrease in reaction time across levels one to three, while a third subject shows a marginally significant decrease.

If eye movements are contributing to the effect of item dispersion, it is important to eliminate the influence of eye movements before the effect is interpreted. For this reason, Experiment 2b replicates the conditions of Experiment 2 under eye movement control. The implications of the observed effect of dispersion (as tempered by the results of the eye movement control) will be discussed at the end of Experiment 2b.

Experiment 2b: Effect of Dispersion Under Eye Movement Control

It is possible that the effect of dispersion observed in Experiment 2 reflects the influence of two different factors. The particularly fast reaction times observed when the cued objects occupy adjacent locations may be due to facilitation from eye movements to the locus of one of the cued objects. This facilitation would be especially strong for all of the cued items (rather than simply one of the subset) when the three items are together in the display. It is possible that this facilitation masks, at least for some subjects, a more general decrease in reaction time as the dispersion of the indexed items increases. Eliminating eye movements, therefore, may reveal an effect of dispersion that is consistent across all levels of the dispersion variable. In order to investigate the potential role of eye movements in the results of Experiment 2, Experiment 2b is a replication of Experiment 2, with eye movements controlled.

Two subjects from Experiment 2 participated in the eye movement control (only two subjects were used because subjects found the task to be both onerous and stressful). Individual subject analyses in Experiment 2 revealed substantial inter-subject differences in the pattern of reaction time effects. Four of the subjects showed a significant effect of dispersion, and four did not. In order to best evaluate the influence of eye movements on the results of Experiment 2, one subject for the current experiment chosen from the group who did not demonstrate a significant effect of dispersion in Experiment 2, and the second subject was chosen from the group who demonstrated an effect of dispersion.

Method

Subjects. Two subjects participated in Experiment 2b. Each subject had also participated in Experiment 2; thus, subjects were practiced at the experimental task. Subjects completed one practice session before starting on 5 experimental sessions. Each experimental session lasted approximately 45 minutes.

Stimuli. Apparatus used to display stimuli and collect reaction times were identical to those used in previous experiments. The stimuli used in Experiment 2b were identical in all respects to those used in Experiment 2.

A Dr. Bouis eye movement monitor was used to monitor fixation. Head position was fixed using a bite bar. Subjects initiated each trial by pressing a button when they were accurately fixating the central cross. Immediately following this button press, the fixation point for the trial was established by measuring eye position for the next 100 msec. Following this period, each trial proceeded exactly as in Experiment 2. Eye position was monitored constantly during the trial; blinks were filtered from the eye movement trace. If, at any time during the trial, the eye moved more than 1.3° from the point of fixation defined for the trial (note that this is .44 of the distance to the objects in the search display under the near radius, and .38 of the distance for the larger radius) the trial was rejected.

Procedure. Each experimental session consisted of a total of 288 trials, defined exactly as in Experiment 2. The number of practice trials was reduced to twelve at the beginning of each session, and five at the point where the search set type changed. Trials were initiated by the subject, using a press of either mouse button. This procedure ensured that the minimum number of trials were lost due to eye movements, because subjects could ascertain that they were fixating the central cross before the trial began. In addition to the regular feedback concerning accuracy of response, subjects were given feedback about the accuracy of fixation. If an eye movement greater than 1.3° occurred at any point during the trial, the trial was rejected and a high-pitched beep was sounded after the subject responded (and after any error feedback) to inform subjects of the rejection.

Results

Trials for which an eye movement occurred were eliminated from the analysis. In addition, as in Experiments 1 and 2, trials immediately following an error response were removed from the calculation, as were trials with a correct reaction time more than 2.5 standard deviations from the cell mean. The eye movement criterion resulted in the rejection of 7.9% of trials for subject JB and 12.7% of trials for subject RE. For each subject, an analysis of variance was conducted with trial status (rejected, not rejected) as the dependent variable and target condition (absent, present), search set type (feature set, conjunction set) and dispersion (0, 1, 2, 3) as independent variables. Neither the analysis for subject JB nor the analysis for subject RE revealed any significant effects. Eliminating trials following an error response and trials more than 2.5 standard deviations from the mean led to the rejection of between 0% of trials (for conjunction search set, dispersion level 2, target present trials) and 10% of trials (for conjunction search set, dispersion level 0, target absent trials) for subject JB, and between .5% of trials (for feature search set, dispersion level 0, target absent trials) and 17% of trials (for feature search set, dispersion level 1, target absent trials) for subject RE.

After eliminating rejected trials, trials immediately following an error response and trials with a correct reaction time greater than 2.5 standard deviations from the cell mean, percent error and average correct reaction time were calculated for each combination of dispersion, search set type and target condition. Results are collapsed across the 5 experimental sessions. The descriptive statistics for subject JB are presented in Table 5, and the descriptive statistics for subject RE are presented in Table 6. Analysis of variance tables are presented in Appendix C.

For each subject, both the reaction time and error results were submitted to analyses of variance, with target condition (target present, target absent), search set type (feature search set, conjunction search set) and dispersion (0, 1, 2, 3) as independent variables. For each subject, the error analysis revealed significant effects of target condition (subject JB: $F_{(1,1255)}=7.47$, $p<.01$, error rates of 3% for target-absent, 6% for target-present; subject RE: $F_{(1,1139)}=17.56$, $p<.01$, error rates of 6% and 13% for target-absent and target-present conditions) and search set type (subject JB: $F_{(1,1255)}=6.54$, $p<.05$, error rates of 3% and 6% for feature subset and conjunction subset conditions; subject RE: $F_{(1,1139)}=7.24$, $p<.01$, error rates of 7% and 12% for feature subset and conjunction subset conditions). In addition, the interaction of target condition by dispersion was significant for subject RE ($F_{(3,1139)}=4.81$, $p<.01$). Error rates for feature subsets were 8%, 9%, 5% and 2% for levels 0, 1, 2 and 3 of

Table 5
Experiment 2b: Descriptive Statistics for Subject JB

Dispersion	Condition Search Set Type	Target Presence	Reaction Time (msec)	s.d.	Percent Errors	s.d.
0	feature	absent	473	*59*	2.6	*16.0*
		present	485	*62*	1.2	*10.9*
	conjunction	absent	566	*89*	5.2	*22.3*
		present	516	*96*	6.3	*24.4*
1	feature	absent	479	*59*	1.3	*11.4*
		present	482	*71*	4.1	*19.9*
	conjunction	absent	561	*95*	2.5	*15.8*
		present	507	*95*	6.3	*24.5*
2	feature	absent	479	*47*	0.0	*0.0*
		present	479	*65*	4.9	*21.8*
	conjunction	absent	583	*95*	4.9	*21.7*
		present	494	*83*	9.8	*29.9*
3	feature	absent	478	*60*	0.0	*0.0*
		present	477	*75*	8.5	*28.1*
	conjunction	absent	562	*96*	5.3	*22.6*
		present	491	*92*	5.1	*22.2*

Table 6
Experiment 2b: Descriptive Statistics for Subject RE

Dispersion	Condition: Search Set Type	Target Presence	Reaction Time (msec)	s.d.	Percent Errors	s.d.
0	feature	absent	550	*85*	3.9	*19.5*
		present	496	*103*	2.9	*17.0*
	conjunction	absent	636	*128*	12.5	*33.3*
		present	492	*84*	10.3	*30.6*
1	feature	absent	525	*68*	3.0	*17.3*
		present	525	*115*	10.8	*31.3*
	conjunction	absent	596	*100*	15.5	*36.4*
		present	519	*109*	14.5	*35.4*
2	feature	absent	521	*69*	4.1	*20.0*
		present	511	*101*	16.2	*37.1*
	conjunction	absent	592	*103*	6.6	*25.0*
		present	500	*105*	20.3	*40.5*
3	feature	absent	527	*78*	1.3	*11.6*
		present	503	*99*	17.1	*40.0*
	conjunction	absent	545	*83*	2.8	*16.4*
		present	502	*84*	15.1	*36.0*

dispersion; for conjunction subsets, error rates were 7%, 13%, 18% and 16% for levels of dispersion 0, 1, 2 and 3.

In Experiment 2, the data for subject JB revealed no main effect of dispersion. There was, however, a significant interaction of target condition by search set type, along with main effects of both these factors. In the current experiment, the analysis of variance for reaction time with target condition (target present, target absent), search set type (feature set, conjunction set) and dispersion (0, 1, 2, 3) as factors revealed the same pattern of effects. The main effect of dispersion does not approach significance ($F_{(3,1201)}$=.736, *n.s.*; the average reaction times are 509 msec, 508 msec, 509 msec and 501 msec for dispersions 0, 1, 2 and 3 respectively). The main effects of target condition and search set type are both significant (for target condition, $F_{(1,1201)}$=46.24, p<.01; for search set type $F_{(1,1201)}$=157.06, p<.01), as is the interaction between these two variables ($F_{(1,1201)}$=59.86, p<.01). The pattern of reaction times in the interaction is similar to that observed in Experiment 2. Average reaction times were 477 msec, 481 msec, 568 msec and 502 msec for feature target absent, feature target present, conjunction target absent and conjunction target present conditions, respectively. Tests of means (by Tukey-Kramer modification of Tukey's HSD) indicate that the reaction time advantage for target present trials is significant only for conjunction search subsets (critical $q_{(.05;4,1201)}$=2.77, observed values of 14.5 for conjunction search sets and -.9 for feature search sets).

In the current experiment, the data from subject RE show a pattern that is different from that demonstrated in the results of subject JB; the same was true in

Experiment 2. In Experiment 2, subject RE demonstrated a significant effect of dispersion, with the reaction time for a dispersion of 2 significantly longer than reaction times for all other dispersions. For subject RE, other significant effects in Experiment 2 included a significant reaction time advantage for feature search subsets, and a significant advantage for target-present reaction times (but no significant interaction of these two factors). In this experiment, the main effect of dispersion was also significant ($F_{(3,1026)}$=3.82, p<.05); the observed pattern of reaction times, however, is different from that in Experiment 2. Average reaction times for dispersions of 0, 1, 2 and 3 are 544 msec, 540 msec, 534 msec and 521 msec in the current experiment. Tests of means (using the Tukey-Kramer modification of Tukey's HSD) reveal that reaction times for dispersions of 0 and 1 are significantly longer than reaction times for dispersions of 3 (critical $q_{(.05;4,1026)}$=2.77; observed values of q were 3.91 for the comparison of dispersions of 0 and 3, and 3.2 for the comparison of dispersions of 1 and 3). No other pairwise comparisons are significant.

The data for subject RE revealed one significant interaction involving dispersion: the interaction of search set type and dispersion ($F_{(3,1026)}$=6.42, p<.01; see Figure 12). Tests of means revealed no significant differences among the various levels of dispersion for feature search sets (average reaction times of 525 msec, 525 msec, 516 msec and 517 msec for dispersions of 0, 1, 2 and 3). In contrast, for conjunction search sets, the average reaction time for dispersion 0 was significantly

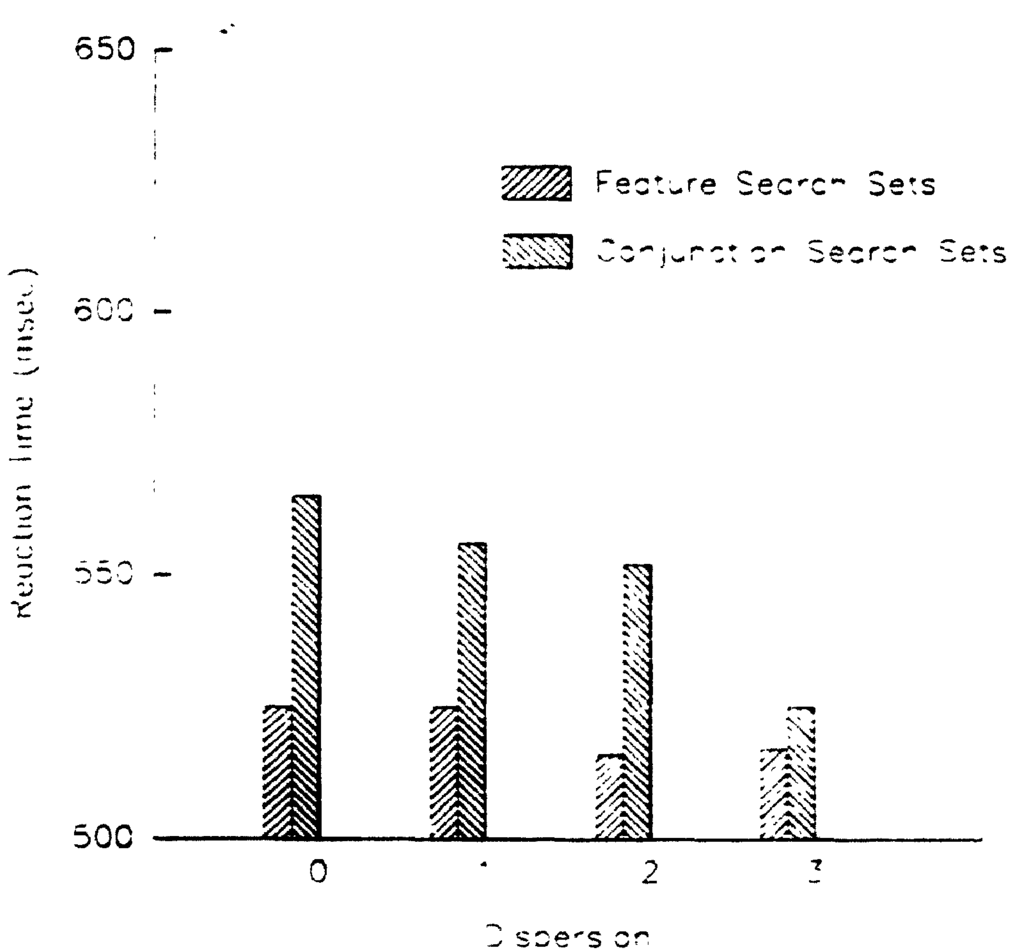

Figure 12. **Experiment 2b: Interaction of dispersion and search set type for subject RE.**

longer than the average reaction time for a dispersion of 3 (average reaction times of 565 msec, 556 msec, 552 msec and 525 msec for dispersions of 0,1,2 and 3; critical $q_{(.05;8,1026)}$=4.29, observed q of [illegible].76 for comparison between dispersions of 0 and 3).

In addition to significant effects involving dispersion, subject RE showed a main effect of target condition ($F_{(1,1026)}$=85.23, p<.01), a main effect of search set type ($F_{(1,1026)}$=23.74, p<.01), and an interaction of these two factors ($F_{(1,1026)}$=31.42, p<.01). For subject RE, the pattern of reaction times for the interaction is similar to both the pattern for subject JB in the current experiment, and similar to the pattern of reaction times observed over subjects in Experiment 2. For conjunction subsets, target-present responses are faster than target-absent responses by 88 msec (mean reaction times of 503 msec and 591 msec respectively, critical $q_{(.05,4,1026)}$=2.77, observed q of 14.66); the difference for feature subsets, at 22 msec, is smaller (though still significant, with a observed q of 3.77; means are 509 msec and 531 msec for target-present and target-absent trials respectively).

Discussion

The reaction time advantage for feature search subsets is maintained when eye movements are eliminated; thus, the dispersion effect observed in Experiment 2 cannot be attributed solely to foveation of one or more of the selected items. Furthermore, the interaction of target condition and search set type (which was significant for only one of the two subjects in Experiment 2) reaches significance for both of the subjects under eye movement control. This replicates the result, observed in Experiment 2, that target-absent responses among conjunction search sets are slowed more than target-absent responses among feature search sets.

Eye movement control in Experiment 2b did not eliminate the main effect of dispersion for the one subject who demonstrated this effect in Experiment 2. The control of eye movements did, however, change one aspect of the effect of dispersion. In Experiment 2, reaction time was speeded when the three objects occupied adjacent locations in the display matrix. Under eye movement control, this effect is eliminated, leaving a main effect of dispersion (for subject RE only) that is characterized by decreasing reaction time as the dispersion of the indexed items increases. Furthermore, this dispersion effect is confined to displays with conjunction search subsets; there appears to be no effect of dispersion when the selected subset contains homogeneous distractors.

It appears that the overall speeding of reaction time at the closest dispersion in Experiment 2 may be attributed to eye movements (by a subset of subjects) to the region of the indexed objects. The control of eye movements does not substantially alter task performance in any other way. It appears that the only performance difference between results of the two experiments (aside from a general speeding of responses that may be attributed to practice) is the elimination of particularly fast responses when the indexed objects occupy adjacent locations in the display. The effect of dispersion will therefore be interpreted in the light of the results of both Experiments 2 and 2b.

The general reduction in reaction time with an increase in the dispersion between selected objects (reliably observed for some, but not all, subjects) argues against the spotlight theory of attention. The spotlight theory suggests that an increase in the spatial dispersion of the items to be processed should result in an increase in reaction time. The effect observed in the current experiment does not fit this prediction. In general, the zoom lens theory would make a prediction similar to that of the spotlight theory. Under the zoom lens theory, reaction time should increase with the dispersion of the items because, as the attentional focus expands to cover all of the relevant items, the limited attentional resources are spread over a wider area. Speed of processing is assumed to be directly related to the concentration of attentional resources; as the limited resources are spread over a wider area, processing should be slowed. Once again, this prediction does not match the observed effect of dispersion.[15]

[15]A variant of the zoom lens model, which assumes that the attentional beam can assume any shape so long as it maintains a convex hull, could possibly account for the results observed in the current experiment. Such an account would only work if the attentional beam had a shape which clearly excluded nontargets when the dispersions were 0 and 3, and only partially excluded them for other dispersions (which could lead to interference, and thus slowed reaction times, in these conditions). This is close to being the case with a minimal convex hull. For example for the three target case a triangular beam shape nicely covers three targets only when they are adjacent and when they are 3 items apart, whereas the edges of the triangular beam get close to the nontargets for dispersions of 1 and 2 (though how close depends on the diameter of the circle of items, the size of the items, and the precision of locating the edges of the triangular beam). This hypothesis does not seem plausible, however. Not only does the hypothesis lack independent motivation, it could not explain the change in the effect of dispersion observed in Experiment 3b when eye movements are eliminated (because there is no reason to assume that this would force observers to change either the size or shape of the attentional beam). Moreover there is independent evidence against a single contiguous region view of attention. In a number of studies of visual tracking (e.g., Intriligator & Cavanaugh, 1992; Sears & Pylyshyn, 1992) as well as studies of subitizing (e.g., Trick & Pylyshyn, 1993) it has been shown that items are indexed separately, and not by a single beam shaped to encompass the indexed items.

Had there been no significant effect of dispersion in the current experiments, it would be possible to argue that the degree of dispersion of the indexed objects was simply too small to have a significant effect on reaction times. The significant dispersion effect, however, reveals generally *decreasing* reaction times with increasing item dispersion (observed for dispersions 1 to 3 in Experiment 2, and dispersions 0 to 3 for one subject in Experiment 2b). This trend provides strong evidence against both the assumption that a single locus of attention is moved (in an analog fashion) to each of the three cued locations in turn and the alternative assumption that a single attentional locus is changed in size to encompass the indexed items.

At the same time, the observed dispersion effect is not predicted by FINST theory. Under FINST theory, it is assumed that an indexed object can be automatically and immediately accessed. Thus, the time required to access each of a set of indexed objects should be independent of the spatial dispersion of the set. In the current experiment, the time required to process the set of FINSTed items decreased as the dispersion of the items increased. This effect may reflect decreases in access time for the set of items as dispersion increases. It is possible, however, that the slowing of reaction time observed when FINSTed items are close together reflects an increase in the time required to *process* the indexed items, rather than an increase in the time required to *access* each item (which is assumed, by the FINST hypothesis, to be independent of inter-item distance).

Many researchers have demonstrated slowing of stimulus identification responses when stimuli to be identified are flanked by distractors demanding an opposite response (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972). In the current experiment, however, the degree of observed interference depends on the distance between FINSTed items, rather than the distance between a particular FINSTed item and its nearest neighbours. In every display, each the twelve possible display positions is occupied by an object. As the dispersion of the cued items increases, the number of uncued objects between FINSTed items also increases, but the distance between each FINSTed item and its nearest neighbours remains the same (because every location in the array is occupied). Thus, the dispersion effect cannot be attributed to changes in the separation of nearest contours of objects in the display. Instead, this effect must be attributed either to selective interference between indexed objects, or to a degree of interference from un-indexed objects that increases as the distance to the nearest indexed object decreases.

It has been demonstrated by several researchers (e.g., Henderson, 1991; Henderson & Macquistan, 1993; Maylor & Hockey, 1985; Schmidt, personal communication, August 18, 1993) that the attentional effects of exogenous cues are not perfectly constrained to the location of the cue, but instead decrease gradually with increased distance from the cue. A gradient model of exogenously-cued attention (as suggested by Henderson, 1991, and elaborated by Henderson & Macquistan, 1993) cannot, by itself, account for the results observed in this experiment. If, however, it is assumed that a similar gradient of facilitation occurs simultaneously at each of the indexed locations, there should be greater interference when the indexed locations are closer together, as observed in Experiments 2 and 2b.

Interference between FINSTed items may result from the particular demands of the cued conjunction search task, which appears to utilize selective registration of the features of FINSTed items. One possibility is that the process of polling the set of FINSTed items for the features they represent may result in a small degree of activation spreading to nearby locations, which might lead to particular enhancement of (and thus interference from) nearby items when they receive the benefit of spreading activation from several nearby FINSTs. This would suggest, however, that the interference effects should be restricted to search among feature search subsets, which presumably relies on the feature registration process; in fact, in Experiment 2b the interference observed for subject RE is restricted instead to conjunction search subsets.

The dispersion effect observed in Experiments 2 and 2b provides strong evidence against both spotlight and zoom lens theories of attention, without exactly conforming to the predictions of FINST theory. FINST theory could accommodate the results if it is assumed that the observed interference between nearby FINSTed items occurs at the level of processing, rather than the level of indexing.

Neither the spotlight theory nor the zoom lens theory, however, can account for the decrease in reaction time as the distance between items increases. Thus, Experiments 2 and 2b provide strong evidence contrary to a theory which proposes a necessarily unitary focus of attention. Instead, the evidence suggests that multiple selected locations in a visual display are accessed through a process different from scanning of a single attentional beam, or expansion (or contraction) of a single attentional focus. The alternative offered by FINST theory is that each selected location receives an index (or FINST) that provides immediate access to the indexed locations. Despite aspects of the data that do not exactly fit this interpretation, FINST theory appears to be the best account of the current results.

Experiment 3: Effect of Number of Indexed Items in Subset Search

The results of Experiments 1, 2 and 2b suggest that subsets of three items are processed as if they are the sole items in the display. This interpretation is based on the result (from Experiment 1) that search is faster when three items are selected from fifteen than when all fifteen elements are potential targets. The interpretation is strengthened by the result (from Experiments 1, 2 and 2b) that, for three-item subsets, search for conjunctively defined targets is faster among feature search subsets as opposed to conjunction search subsets.

Theories of visual search (e.g., FIT, Treisman & Gelade, 1980; Guided Search, Wolfe et al., 1989; and a competitive interaction model proposed by Duncan & Humphreys, 1989) suggest that search should be faster among homogenous distractors than among mixed distractors. Each of these models predicts that the performance difference between feature search displays (with homogenous distractors) and conjunction search displays (with mixed distractors) should increase with the number of items. FIT and the Guided Search model further predict that reaction times will increase more with each added distractor for target-absent responses than for target-present responses in conjunction search. Experiment 3 attempts to demonstrate these reaction time effects in a selective conjunction search task.

Previous research (e.g., Pylyshyn & Storm, 1988; Yantis & Johnson, 1990) has suggested the upper limit for the number of items that can be selected simultaneously to be approximately four or five, although it is entirely possible that the number of accessible FINSTs will vary with task difficulty (see Yantis & Johnson, 1990). The search task in the current experiment is arguably simpler than the letter discrimination task of Yantis and Johnson, and the tracking task of Pylyshyn and Storm; therefore, an upper limit of five cued items was used in the current experiment, and the range of number of cued items investigated is 2 to 5.

Pilot research with the selective search task indicated that selection of a subset of items becomes increasingly difficult as the number in the subset increases. Two aspects of the experimental design aid and encourage subjects to process selectively late-onset items. First, a small number of highly practiced subjects serve as the observers for this experiment, under the assumption that experience (especially for larger numbers of cues) will lead to an improvement in the ability to maintain indexes on a larger number of cued objects. Second, the displays are designed so that the search task cannot be accurately completed *unless* the identity of the cued items is maintained.

Experiment 3 provides a further test of the hypothesis that indexed items are treated as if they are the only items in the display. There are three independent variables manipulated in this experiment: number of cues (2, 3, 4, 5); search set type (feature set, conjunction set); and target condition (target present, target absent). It is predicted that the pattern of reaction times for selective search observed over increases in the number of indexed items will resemble the pattern of reaction times predicted by models of non-selective visual search. Based on models of visual search (e.g., FIT, proposed by Treisman & Gelade, 1980; Guided Search, proposed by Wolfe et al., 1989; and a competitive interaction model proposed by Duncan & Humphreys, 1989), it is predicted that: 1) feature search subset reaction times will increase very little with each added distractor, and reaction times for feature search target-present and target-absent responses will tend to increase in parallel; 2) conjunction search subset reaction times will show a much larger increase with each added distractor, and reaction times for target-absent responses will show a greater effect than do target-present responses.

Method

Subjects. Four subjects participated in the experiment. Three of the subjects were female, and one was male. The subjects ranged in age from 22 to 36. Each subject participated in one full practice session and six experimental sessions. The length of each experimental session was approximately 45 minutes.

Stimuli. With respect to the items, the matrix of display positions, the cuing procedure and the sequence of events on each trial, the stimuli used in Experiment 3 were identical to those used in Experiment 1. The following description explicitly notes those ways in which Experiment 3 differs from Experiment 1.

To encourage subjects to maintain FINSTs on the indicated objects, displays in the current experiment were constructed so that it was not possible to do the task unless the FINSTs were accurately maintained. Each display included a number of false targets among the uncued objects. Subjects were required to indicate whether a target was included *among the set of indexed items*; the modification of the displays ensured that the entire display was not being searched in lieu of selective search over the indicated subset.

Each display consisted of a total of 24 items: 8 target items, and eight of each type of distractor (that is, eight items sharing colour but not orientation with the target, and eight sharing orientation but not colour with the target). A subset of items, varying in number from 2 to 5, was cued (by late onset) in each display. This subset of items formed either a feature search subset (homogenous distractors) or a conjunction search subset (heterogenous distractors). For the target-present trials within each combination of number of cues and search set type, the target item among the cued subset appeared once in each of the thirty-six potential display positions. The positions of all other objects (both cued and uncued) were chosen randomly (without replacement) from the remaining 35 positions. An equal number of target-absent displays was formed by switching the locations of the target item among the cued subset and an appropriately chosen distractor from among the uncued items.

Procedure. There were three independent variables manipulated in each experimental session: number of cues (2, 3, 4, 5); search set type (feature, conjunction); and target condition (target present, target absent). Each session included 36 trials in each possible combination of number of cues, search set type and target condition. For target-present trials, the target occupied each possible display position once in the 36 trials for each type of display (number of cues by search set type). An equal number of negative trials was constructed by replacing the target (among the cued objects) with an appropriate distractor. This resulted in a total of 576 experimental trials per session.

Trials were blocked by number of cues (the order was determined randomly), and, within each number of cues, blocked by search set type (again, order was determined randomly). Target-present and target-absent trials were randomly intermixed within each block. Changes in the number of cues were preceded by a practice block of 36 trials. Within each number of cues, changes in the search set type were preceded by a practice block of 18 trials. Rest breaks were provided at the beginning of each block.

Barring the exceptions explicitly noted below, the task and instructions to subjects were identical to those of Experiments 1 and 2. In this experiment, subjects were instructed to search for targets *only* among the cued subset of objects; they were further informed that the uncued objects would include a number of false targets. Subjects were explicitly instructed not to respond if they felt they could not accurately identify all members of the cued subset of objects (surprisingly, this option was very rarely used, although subjects often made errors for the larger subsets; perhaps they were unaware that they had not accurately indexed the cued objects).

Each subject participated in a total of seven sessions. The first of these sessions was treated as practice; the data from these practice sessions are not included in the results.

Results

The data from four subjects are reported in this experiment.[16] The proportion of errors and average reaction time were calculated for each subject in every combination of number of cues (2, 3, 4, 5), search set type (feature set, conjunction set), target condition (target present, target absent) and level of practice (less, more). The data from the second, third and fourth sessions were collapsed to form the first level of practice,[17] and the data from the fifth, sixth and seventh sessions were collapsed to form the second level of practice (the first session was used to acquaint subjects with the task, and the data from that session are therefore not included in the analysis).

Errors are defined differently in the current experiment than in previous experiments in this thesis. Displays in the current experiment include false targets among the uncued items; the task of the subject is to identify whether a target is included *among the indexed subset*. Thus, in the current experiment an error is defined either as a 'target in set' response when there was no target in the subset, or a 'no target in set' when a target was in fact included among the indexed items. As in Experiments 1, 2 and 2b, trials immediately following an error were discarded from

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[16]A fifth subject participated in three sessions of the experiment. She proved, however, unable to complete the task, particularly with a larger number of cues. In addition, the pattern of reaction times for this subject was different from the patterns observed for all other subjects, who showed a great deal of similarity among themselves. Finally, this subject demonstrated unusually long reaction times. On the basis of these three differences, this subject was eliminated from the experiment.

[17]Due to an unexpected lack of space on the computer hard drive, the data from the fourth session for the subject BA were not recorded. For this subject, therefore, the first level of practice includes the data from sessions two and three.

the analysis, as were any trials in which the reaction time for a correct response fell more than 2.5 standard deviations from the cell mean. These criteria led to the rejection of between 4.4% of trials (3 cues, conjunction search set, target absent trials) and 19.5% of trials (for 5 cues, feature search set, target absent trials). Reaction time and error data for all subjects were submitted to a four-way repeated measures analysis of variance, with number of cues (2, 3, 4, 5), search set type (feature, conjunction), target condition (target present, target absent) and level of practice (less, more) as independent variables; error data were submitted to an analogous analysis of variance. Descriptive statistics for the error data are presented in Table 7, and descriptive statistics for the reaction time analysis are presented in Table 8. Analysis of variance summary tables are presented in Appendix D.

The analysis of variance for error data (across subjects) revealed a number of significant effects. There is an observed decrease in the proportion of errors as practice increases (6.6% errors for less practice, 4.9% errors for more practice, $F_{(1,3)}$=17.19, p<.05). Subjects make fewer errors in the feature search set condition as opposed to the conjunction search set condition (4.8% errors for feature search sets, 6.7% errors for conjunction search sets; $F_{(1,3)}$=11.01, p<.05), and fewer errors on target-absent trials, as compared to target-present trials (6.9% errors for target present, 4.6% errors for target absent, $F_{(1,3)}$=24.02, p<.05). Finally, there is a significant effect of number of cues ($F_{(3,9)}$=15.82, p<.05); there is a tendency for errors to increase as the number of cues increases (2.3% errors for two cues, 3.1% errors for three cues, 6.3% errors for 4 cues and 11.3% errors for five cues). There are also two significant

Table 7
Experiment 3: Percent Error Descriptive Statistics

Number of Cues	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*
Less Practice								
2	3.3	*2.6*	1.8	*1.7*	1.5	*0.6*	2.8	*1.5*
3	3.0	*1.4*	2.0	*1.6*	3.3	*0.5*	5.0	*4.5*
4	3.5	*2.4*	7.5	*1.7*	9.5	*4.8*	10.3	*5.0*
5	6.8	*4.8*	14.8	*1.0*	13.0	*1.4*	16.5	*5.3*
More Practice								
2	1.8	*1.0*	3.3	*2.2*	1.0	*0.0*	1.8	*2.2*
3	1.8	*1.0*	2.8	*1.3*	4.0	*3.4*	2.5	*2.4*
4	1.3	*1.0*	5.5	*1.3*	4.0	*2.9*	8.5	*3.5*
5	5.0	*4.8*	11.0	*4.2*	10.3	*11.3*	13.3	*6.9*

Table 8
Experiment 3: Reaction Time Descriptive Statistics

Number of Cues	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*
Less Practice								
2	570	*78*	531	*63*	573	*83*	528	*66*
3	569	*64*	562	*50*	655	*89*	620	*93*
4	585	*65*	597	*48*	718	*91*	635	*89*
5	598	*62*	593	*22*	762	*109*	662	*76*
More Practice								
2	541	*56*	515	*58*	551	*60*	511	*41*
3	539	*35*	524	*52*	614	*57*	567	*43*
4	552	*33*	552	*53*	668	*77*	606	*46*
5	563	*41*	554	*38*	700	*50*	620	*59*

interactions in the error analysis: number of cues by search set type ($F_{(3,9)}$=5.47, p<.05) and number of cues by target condition ($F_{(3,9)}$=16.26, p<.01). The increase in errors over number of cues is greater for conjunction search sets (error rates of 1.8%, 3.9%, 8.1% and 13.3% for 2, 3, 4 and 5 cues) than for feature search sets (error rates of 2.8%, 2.4%, 4.5% and 9.4% for 2, 3, 4 and 5 cues). Error rates for target absent trials (2.2%, 3.0%, 4.6% and 8.8% for 2, 3, 4 and 5 cues) increase at a slower rate than do error rates for target present trials (2.4%, 3.2%, 8.0%, 13.9% for 2, 3, 4 and 5 cues).

The results of the reaction time analysis reveal the predicted interaction of number of cues, search set type and target condition ($F_{(2,6)}$=19.06, p<.01). The significant main effects of number of cues ($F_{(3,9)}$=21.97, p<.01), search set type ($F_{(1,3)}$=31.99, p<.05) and target condition ($F_{(1,31.45)}$=11.94, p<.05) are subsumed under this significant three-way interaction, as are the interactions of number of cues by search set type ($F_{(3,9)}$=13.54, p<.01), number of cues by target condition ($F_{(3,9)}$=4.18, p<.05), and search set type by target condition ($F_{(1,3)}$=66.95, p<.01).

The three-way interaction, presented in Figure 13, reveals the predicted pattern of reaction times. In particular, the effect of number of cues appears to be greater for conjunction search sets that for feature search sets. Furthermore, within the conjunction search sets there is a greater effect of number of cues for target absent trials as opposed to target present trials. To explore this interaction further, the effect of number of cues was examined within each combination of search set type and target condition using Tukey's HSD (critical $q_{(.05,16,12)}$=5.95). For feature search sets, the difference in reaction time between the two cue condition and the five cue condition

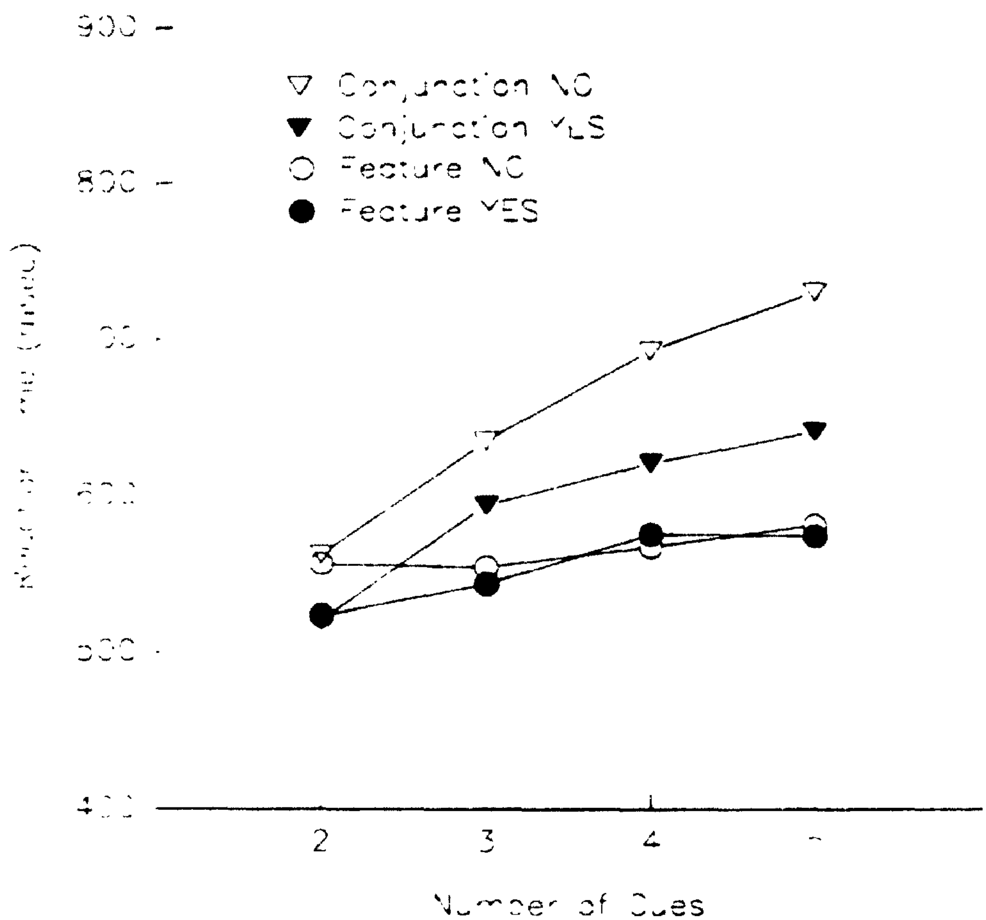

Figure 13**. Experiment 3: Interaction of number of cues, search set type and target condition.**

did not reach significance for either target absent trials (means of 556 msec and 581 msec for two cues and five cues respectively, $q_{(16,9)}$=1.41) or target present trials (means of 523 msec and 574 sec for two cues and five cues respectively, $q_{(16,9)}$=2.88). In contrast, for conjunction search sets both differences reached significance (for target absent trials, means of 562 msec and 731 msec for two cues and five cues respectively, $q_{(16,9)}$=9.54; for target present trials, means of 520 msec and 641 msec for two cues and five cues respectively, $q_{(16,9)}$=6.83). The estimated reaction time slopes (calculated by applying a least squares linear regression to the averages across subjects) reflect the smaller effect of increases in number of cues for feature search sets. For target absent conjunction set searches and target present conjunction set searches, the slopes were 56.5 msec/item (accounting for 98% of the variance) and 38.9 msec/item (accounting for 90% of the variance), respectively (ratio of target absent slope to target present slope is 1.45:1). The slopes for target absent feature set searches and target present feature set searches are 9 msec/item (accounting for 85% of the variance) and 18.5 msec/item (accounting for 89% of the variance), respectively (ratio of target absent slope to target present slope is .49:1).

No other effects were significant in the reaction time analysis. Given the reported difficulty of the task, it is surprising that the effect of practice on reaction time was only marginally significant ($F_{(1,3)}$=6.74, $.05<p<.1$). The pattern of reaction times for this marginal effect, however, suggests an overall decrease in reaction time with an increase in practice; this is consistent with the interpretation that selective search becomes more efficient with practice (means were 610 msec for less practice, 573 msec for more practice).

Separate analyses for individual subjects supported the conclusion that the effect of number of cues differed both by search set type and by target condition. Analyses of variance were computed for each subject over reaction times for individual correct trials. Independent variables in the analyses were number of cues, search set type, target condition and level of practice. Table 9 indicates the significant effects within each individual subject analysis (analysis of variance tables for individual subjects are included in Appendix D).

The three-way interaction of number of cues, search set type and target condition was significant for each of the four subjects (subject JB: $F_{(3,2994)}=7.36$, $p<.01$; subject BA: $F_{(3,2395)}=9.29$, $p<.01$; subject FM: $F_{(3,2978)}=3.07$, $p<.05$; subject JL: $F_{(3,3131)}=9.36$, $p<.01$). Furthermore, the pattern of reaction times in the interaction is similar across the four subjects (see Figures 14 to 17). Table 10 presents the slopes and slope ratios calculated for individual subjects (over the mean reaction times within each combination of number of cues, search set type and target condition). Note that, although there is a great deal of variability between subjects in the calculated slopes, the slopes for the conjunction search set are consistently higher than slopes for feature search sets; furthermore, the slopes for target-absent conjunction search sets are consistently greater than slopes for target-present conjunction search sets.

Table 9
Experiment 3: Significant Effects for Individual Subject Reaction Time Analyses

	Subject			
	JB	BA	FM	JL
Main Effects				
Number of Cues(C)	**	**	**	**
Search Set Type(T)	**	**	**	**
Target Presence(P)	*	**	**	**
Level of Practice(Pr)	**	**	**	**
2-Way Interactions				
C×T	**	**	**	**
C×P			*	
C×Pr	*	**	**	**
T×P	**	**	**	**
T×Pr			**	*
P×Pr	**			*
3-Way Interactions				
C×T×P	**	**	*	**
C×T×Pr			*	**
C×P×Pr				*
T×P×Pr			*	**
4-Way Interactions				
C×T×P×Pr	**			**

* p<.05
** p<.001

Table 10
Experiment 3: Slopes and Slope Ratios for Individual Subjects

	Feature Search Set					Conjunction Search Set				
	Target Absent		Target Present		Slope Ratio	Target Absent		Target Present		Slope Ratio
Subject	Slope	% Var	Slope	% Var		Slope	% Var	Slope	% Var	
JB	12.8	95	26.1	90	.49	85.6	99	63.6	99	1.34
BA	4.6	26	18.9	83	.24	42.4	99	24.3	92	1.74
JL	14.0	96	25.1	99	.56	51.7	96	39.7	95	1.30
FM	3.4	11	2.0	3	1.70	42.9	75	26.3	47	1.63

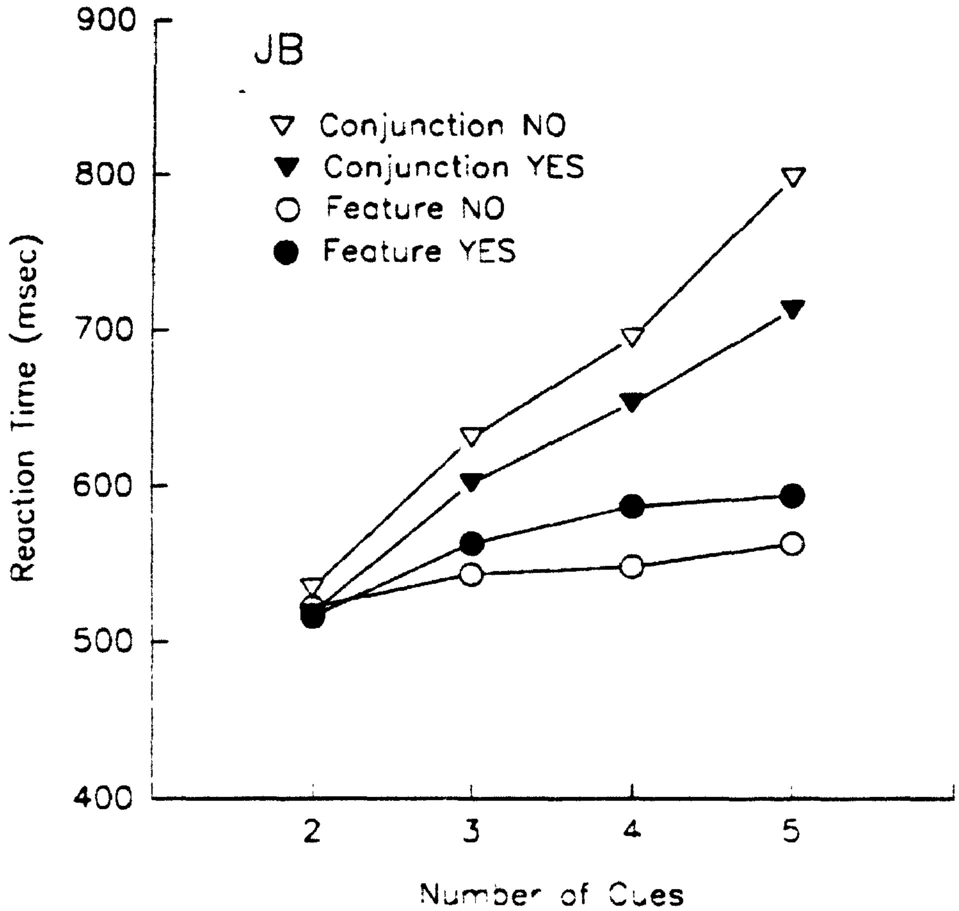

Figure 14. Experiment 3: Interaction of number of cues, search set type and target condition for subject JB.

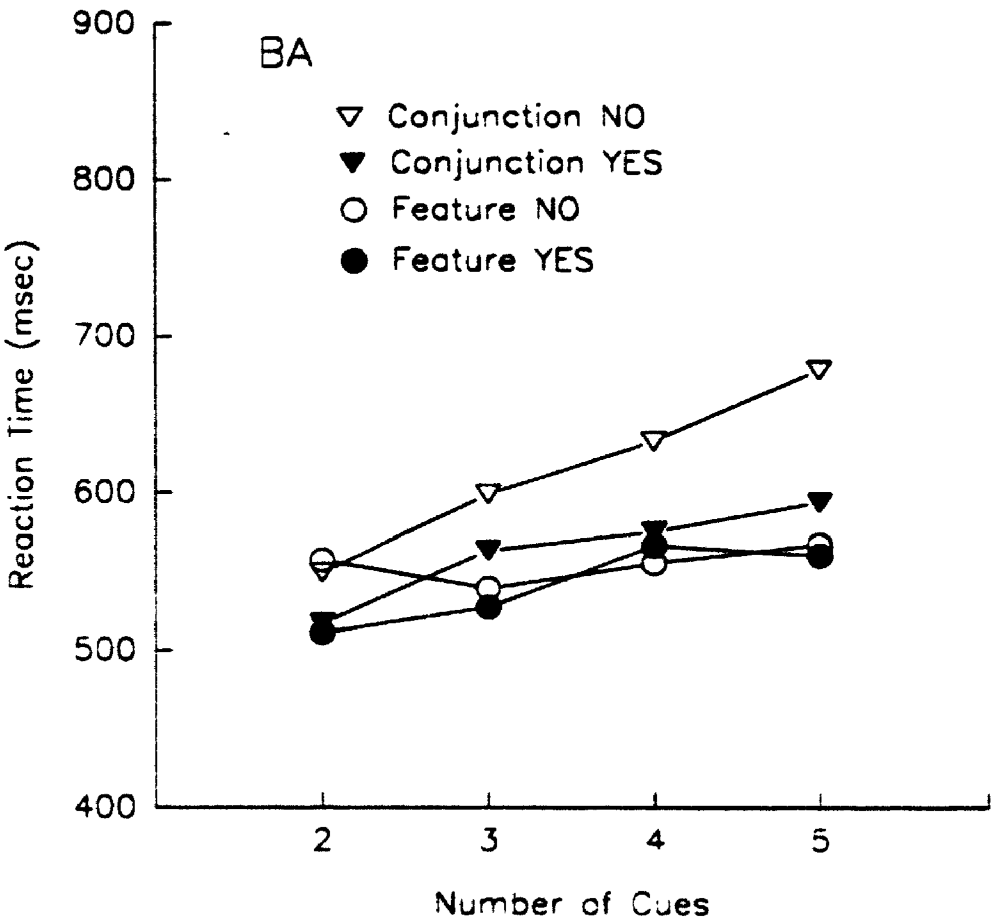

Figure 15. **Experiment 3: Interaction of number of cues, search set type and target condition for subject BA.**

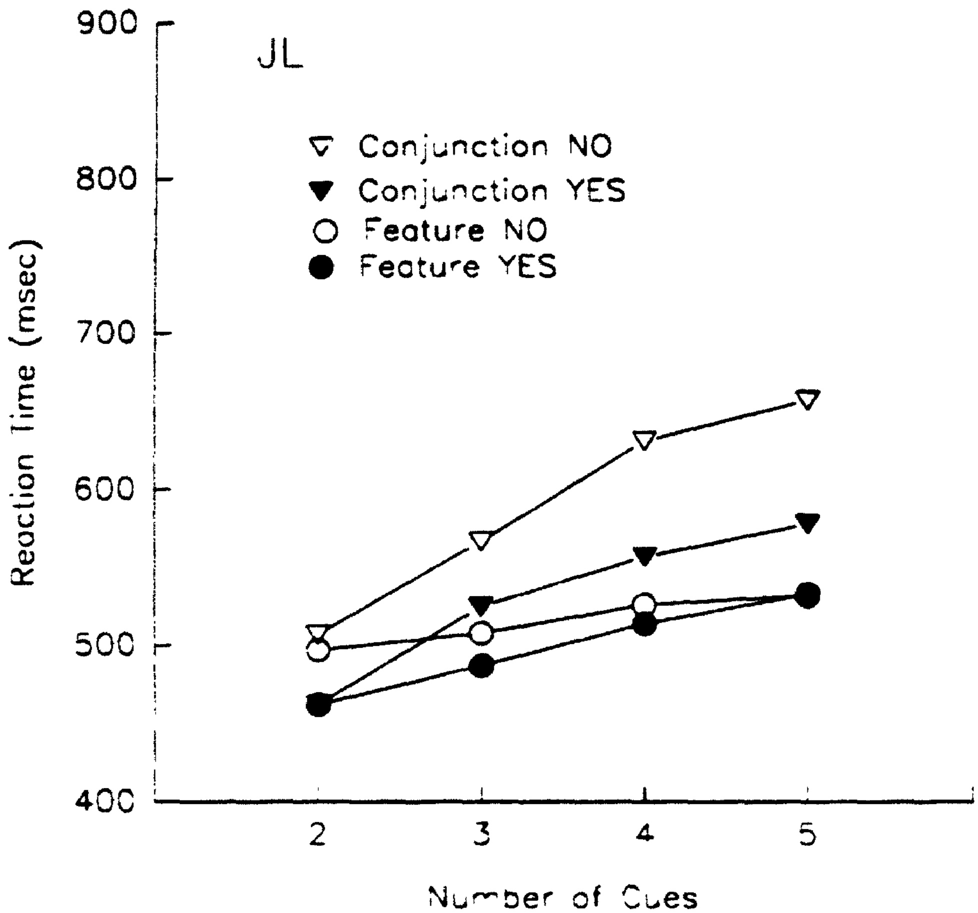

Figure 16. **Experiment 3: Interaction of number of cues, search set type and target condition for subject JL.**

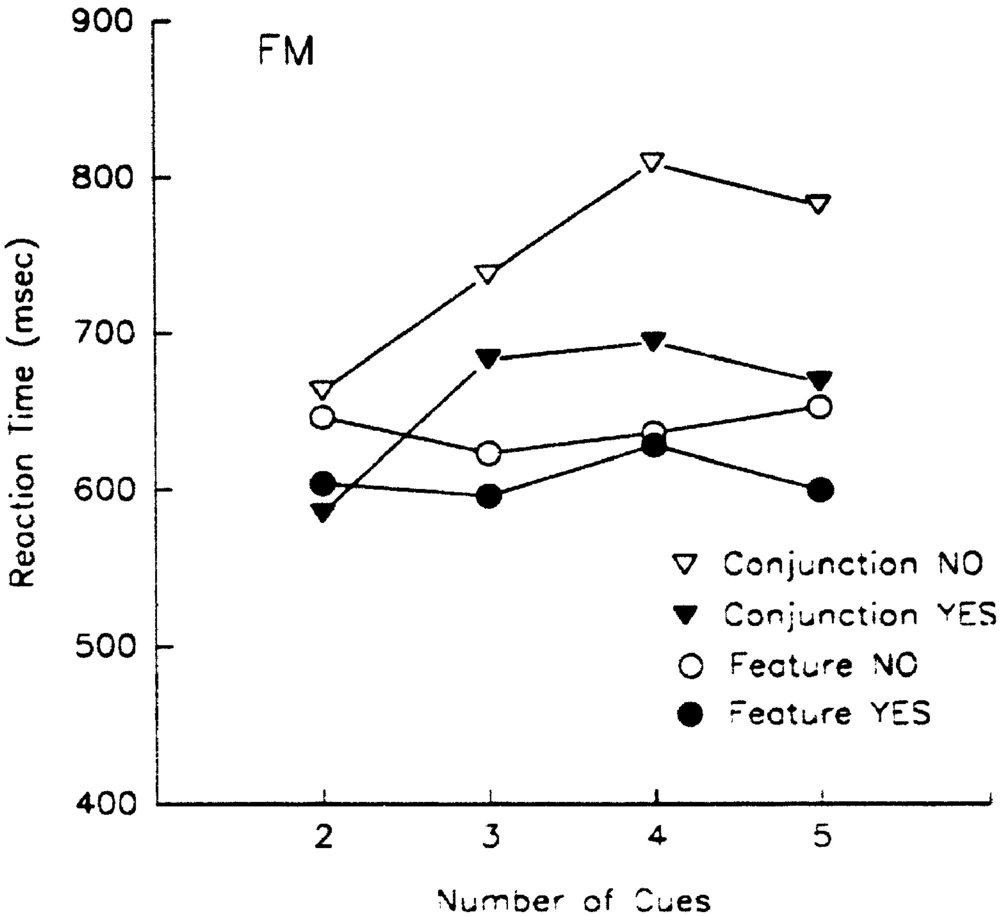

Figure 17. **Experiment 3: Interaction of number of cues, search set type and target condition for subject FM.**

Discussion

The results of this experiment provide clear evidence that search for conjunctively defined targets is faster among feature search subsets as compared to conjunction search subsets, replicating the results of Experiments 1, 2 and 2b. Experiment 3 extends this result to larger numbers of cued items, suggesting that observers may be able to selectively process as many as five (and possibly more) items in a larger display.

In most respects, the significant interaction of number of cues, search set type and target condition, fits the pattern generally observed in visual search. As predicted, reaction time for search among conjunction subsets increases with an increase in the number of cued items, and the per-item increase is greater for target-absent trials (at 56.5 msec/item) than for target-present trials (at 38.9 msec/item). Search among feature search subsets shows less influence of the number of indexed items; particularly for target-absent trials, the per-item reaction time increase (at 9 msec/item) is very small. Target-present feature trials, however, show an unexpectedly large effect of number of indexed items. On average, reaction times in this condition increase by 18.5 msec per added item.

The significant three-way interaction is consistent with effects predicted by models of visual search. This provides further support for the interpretation that indexed items are treated as if they are the only items in the display, extending this result to indexed subsets that are larger in number than those examined in earlier experiments. There is, however, at least one aspect of these results which does not fit predictions of models of visual search. The unusual result is the relatively large reaction time effect for the feature search target-present trials.

This unusual result could be the result of the small size of the search set (cf. Pashler, 1987). Alternatively, the reaction time slope for target-present feature search trials may result directly from the selective search process. If this second alternative holds, the current results cannot be attributed as unequivocal support for the hypothesis that indexed items are the only potential targets for attentional processes, thereby acting as if they are the only items in the display.

Therefore, before the current results are interpreted, it must be determined whether the pattern of reaction times observed in this experiment match the pattern that would result from searches among displays containing only the subset of items. To this end, Experiment 3b examines search among small numbers of abrupt onset items when the search displays do not also include other uncued distractors.

Experiment 3b: Search Among Small Numbers of Items

Although the results of Experiment 3 are generally consistent with predictions based on models of visual search, there is at least one aspect of these results (the relatively large reaction time slope for target-present feature subset responses) that is not predicted by those models. This unusual result has raised two related questions. The first is the question of whether search over an indexed subset is in fact similar to search when these indexed items are the only items in the display. The second is the question of whether models of visual search should be expected to predict performance accurately in the current displays.

Upon reflection, there are at least two reasons to question the predictive validity, in the current context, of models of visual search. One of these reasons arises from the nature of the displays in the current experiments. The indexed stimuli in the current experiments appear briefly as place holders before undergoing a change to become search stimuli. In most visual search experiments, the stimuli do not change after they appear in the display. It is known that the characteristics of the search process are sensitive to a wide range of experimental parameters (see, for example, Treisman & Gormican, 1988). Therefore, it is possible that this difference in presentation method may have an effect on search performance, making performance with the current stimuli much different from that predicted by models of visual search.

Another reason to question the predictive validity of existing models is that these models are designed to predict search performance among relatively large numbers of items, while the search sets in these experiments include a small number of items. There is some evidence, however, that search among small numbers of items may rely on processes that are different from those used in displays including larger numbers of items. For example, Pashler (1987) investigated conjunction search in displays including up to twenty-four items. For displays including more than eight items, his results replicate those observed in most investigations of conjunction search, suggesting a serial, self-terminating search process. In displays with fewer items, however, the conjunction search process appears to be parallel, self-terminating and capacity-limited. On the basis of these results, Pashler proposes an alternative model for conjunction search. In his model, small groups of items (numbering eight or less) are processed in parallel, and tnis parallel process is applied sequentially across the display until either a target is found, or all items have been searched. This model produces parallel search over displays of few items, and serial search over displays including larger numbers of items. It is interesting to note that Pashler proposes an upper limit to the number of items that are processed in parallel (eight or less) that is close to the number of FINSTs proposed on the basis of independent evidence (e.g., Pylyshyn & Storm, 1988; Yantis & Johnson, 1990). The parallel aspects of Pashler's results (and the model he proposes) may reflect the selective attentional processing of indexed items; the serial aspect of the results (and model) may reflect the time required to reassign FINSTs once the items they index have been processed.

It is possible that conjunction search over displays of the indexed items alone will produce results that differ from those observed in Experiment 3. Furthermore, it is possible that this type of search will also differ from predictions of visual search models in ways the results of Experiment 3 did not. Experiment 3b is designed to test these possibilities, and to provide the most appropriate comparison for the results of Experiment 3. In this experiment, observers are asked to search over displays that are identical, except for the removal of the uncued distractors, to the displays of Experiment 3. The reaction time effects observed in the current experiment will therefore provide accurate information about the predicted effects of Experiment 3.

To the extent that models of visual search are able to predict performance in the slightly unusual search displays in these Experiments, the results of Experiment 3b should match those predicted for Experiment 3. Therefore, it is predicted that: 1) feature search subset reaction times will increase very little with each added distractor, and reaction times for feature search target-present and target-absent responses will tend to increase in parallel; 2) conjunction search subset reaction times will show a much larger increase with each added distractor, and reaction times for target-absent responses will show a greater effect than do target-present responses. Furthermore, under the hypothesis that indexed items are selectively processed, behaving essentially as if they are the only items in the display, it is predicted that the pattern of results in the current experiment will match that observed in Experiment 3. In particular, the unexpected slope for feature search target present trials should be replicated in the current experiment.

Method

Subjects. Four subjects participated in Experiment 3b: each was experienced, through selective search experiments, with the displays and the task used in the current experiment.[18] Three of the subjects (JB, JL and BA) had participated in the seven sessions of Experiment 3.[19] The fourth subject (RE) participated in Experiments 1,2 and 2b (the six-session eye movement control for Experiment 2). Thus, each of the four subjects had a similar level of practice.

Stimuli. Displays in Experiment 3b were identical in every respect to displays used in Experiment 3 with the sole exception that uncued distractors were removed from each display. Thus, each display included a total of 2, 3, 4 or 5 items (depending on the number of cues). A figure-X place holder appeared at the location of each object 100 msec before the change to the search display, and 1500 msec after the tone indicating the beginning of the trial. One hundred milliseconds later, all place holders changed to search stimuli. The search task was conducted over this set of stimuli.

Procedure. Practice trials between blocks were reduced from 36 to 5. In all other respects, the procedure used in Experiment 3b was identical to that used in Experiment 3.

[18]Data was also collected, in the same task, from four inexperienced subjects. Their results, however, proved uninterpretable, and they were dropped from the experiment.

[19]The fourth subject in Experiment 3, FM, was not available to participate in the current study.

Results

Average reaction time and proportion errors were calculated for each subject in each combination of item numerosity (2, 3, 4, 5), search set type (feature set, conjunction set) and target condition (target present, target absent). Trials with a correct reaction time more than 2.5 standard deviations from the cell mean were eliminated from the calculation, as were trials immediately following an error response. The proportion of trials dropped on the basis of these two criteria ranged from 3.5% (for 4 cues, feature subset, target present trials) to 7.6% (for 5 cues, conjunction subset, target present trials). Error descriptive statistics are presented in Table 11, and reaction time descriptive statistics are presented in Table 12. Summary tables for the analyses of variance discussed in this chapter are presented in Appendix E.

The error analysis revealed no significant effects.

The reaction time analysis revealed three significant main effects (item numerosity: $F_{(3,9)}=38.38$, $p<.01$; search set type: $F_{(1,5)}=57.35$, $p<.01$; target condition: $F_{(1,3)}=11.18$, $p<.05$). In each case, the reaction time difference was in the expected direction. The main effects of target condition and search set type lead to the following interpretations. Subjects were generally faster to respond when there were fewer items in the display: average reaction times for the four levels of item numerosity were 504 msec, 544 msec, 549 msec and 584 msec for 2, 3, 4 and 5 items respectively. Tests of means using Tukey's HSD (critical $q_{(.05, 4,9)}=4.41$) revealed that all pairwise differences were significant except the comparison of the three-item and four-item trials (observed q's were 10.78 for 2 versus 5, 6.06 for 2 versus 4, 5.39 for

Table 11
Experiment 3b: Error Descriptive Statistics

Number of Cues	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*	Errors (%)	*s.d.*
2	1.5	*1.7*	3.8	*3.8*	3.0	*2.4*	3.0	*6.0*
3	1.5	*3.0*	3.8	*1.5*	1.5	*3.0*	4.5	*5.7*
4	1.5	*1.7*	3.0	*6.0*	0.0	*0.0*	7.5	*5.2*
5	0.8	*1.5*	6.8	*6.7*	4.3	*5.3*	7.5	*3.9*

Table 12
Experiment 3b: Reaction Time Descriptive Statistics

Number of Cues	Feature Search Set				Conjunction Search Set			
	Target Absent		Target Present		Target Absent		Target Present	
	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*	RT (msec)	*s.d.*
2	521	*30*	468	*14*	529	*21*	499	*34*
3	519	*39*	508	*12*	589	*25*	561	*14*
4	509	*32*	503	*6*	618	*21*	567	*21*
5	538	*35*	537	*17*	650	*27*	609	*52*

2 versus 3, 5.31 for 3 versus 5, and 4.71 for 4 versus 5). Subjects were faster to respond to target-present trials (532 msec) than to target-absent trials (559 msec), and faster to respond to feature search set trials (513 msec) than to conjunction search set trials (578 msec). In addition to these significant main effects, there was a significant interaction of item numerosity by search set type ($F_{(3,9)}$=13.13, p<.01). Tests of means (using Tukey's HSD; critical $q_{(.05;\ 8,18)}$=4.82) indicated that, for conjunction search sets, all pairwise comparisons were significant except the comparison of three-item to four-item trials (observed q's: 2 versus 5, 16.72; 2 versus 4, 11.39; 2 versus 3, 8.79; 3 versus 5, 7.93; 3 versus 4, 2.60; 4 versus 5, 5.35). For the feature search sets, only the differences between the two-item and five-item trials, and the difference between the three-item and five items trials reached significance (observed q's: 2 versus 5, 6.20; 3 versus 5, 3.46). Finally, the three-way interaction of item numerosity, search set type and target condition was marginally significant ($F_{(3,9)}$=3.26, .05<p<.1). Within this marginal interaction (presented in Figure 18), reaction time slopes (over number of items) were calculated for each combination of search set type and target condition. Calculated slopes for feature search sets were 4.1 msec/item for target absent trials and 20.2 msec/item for target present trials (the ratio of negative slope to positive slope is 0.2:1), and slopes for conjunction search sets were 38.5 msec/item for target absent trials and 33.5 msec/item for target present trials (the ratio of slopes is 1.2:1).

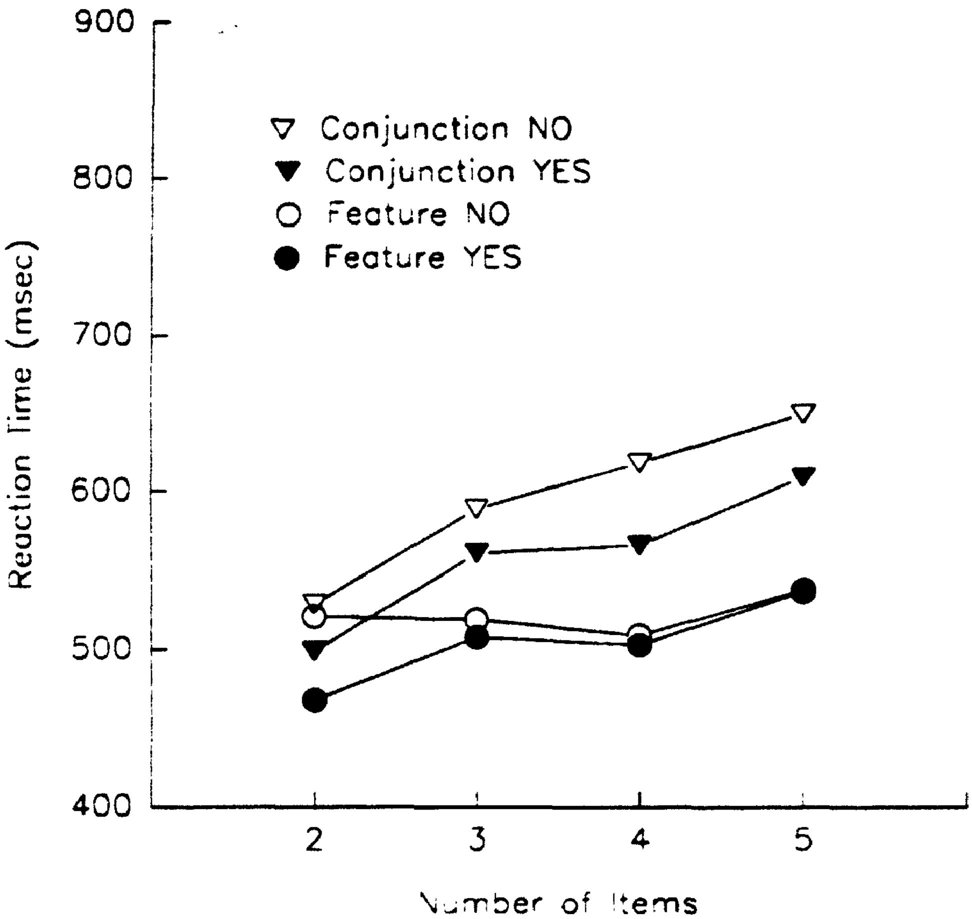

Figure 18**. Experiment 3b: Marginal interaction of number of cues, search set type and target condition.**

Discussion

The results of this experiment confirm that search performance among small numbers of abrupt onset items is, for the most part, predicted by models of visual search. In particular, search is generally faster for feature displays than for conjunction displays, and target-present responses are faster than target-absent responses. The reaction time advantage for feature displays increases with the number of items in the display (at least up to the maximum of five items used in this experiment). Finally, for the conjunction displays, target-absent responses show a greater effect of number of items than do target present responses.

The three-way interaction of item numerosity, search set type and target condition was marginally significant in the current experiment. Analysis of the reaction time slopes for each combination of search set type and target condition reveals a pattern similar to that observed in Experiment 3. In addition to the results noted above, which are consistent both with models of visual search and with the results of Experiment 3, there is the following similarity between the results of these experiments. For feature search sets, the target present slope (20.2 msec/item) is substantial, and larger than the target absent slope (4.1 msec/item), as reflected in the slope ratio (at .2:1) that is less than one.

Thus, most aspects of search performance in Experiments 3 and 3b conform to predictions of theories of visual search. This suggests that neither the relatively small numbers of items nor the unusual presentation procedure radically alter the process of visual search. Furthermore, the experienced subjects who participated in this experiment show a pattern of results very similar to that observed, in Experiment 3, for selective search. In particular, the unexpectedly large reaction time increase for target-present feature search trials is replicated in the current experiment. Search among subsets of items in a larger display is very similar to search in displays including only the subset of items (and no uncued distractors).

The unexpected result among feature search subsets (that is, the degree of positive slope for the target-present condition, especially in comparison to the relatively small slope in the target-absent condition) might be explained by the hypothesis that, at least on some subset of trials, subjects actively confirm the impression that a target is included among the indexed subset. At first glance, it might appear ad hoc, if not opportunistic, to claim response confirmation only in the case of the target-present condition for feature search subsets. Target-present and target-absent feature subset displays, however, differ in one additional way: item homogeneity. In the target-absent displays, all FINSTed objects are identical (since all are distractors, and distractors in this condition are homogeneous). In contrast, two of the three FINSTed items in the target-present displays are identical distractors, but the third is a target, and thus different.

Response certainty in the target-absent condition may be based on negative responses to either a query concerning the presence of the target colour, or a query concerning the presence of the target orientation. When a target is present, both the query concerning the target colour and the query concerning the target orientation will receive positive responses, as will one of a query concerning non-target colour and a query concerning non-target orientation. It is logically impossible for this set of features to be registered without the presence of a target among the items; this reasoning, however, may not be immediately or automatically available to the decision-making process. Under these circumstances, the presence of a target may be confirmed by a serial search of the FINSTed objects on some (or even all) target-present trials, resulting in a steeper reaction time slope for the feature search target-present condition as opposed to the target-absent condition.

A related hypothesis is based on the results of Sagi and Julesz, 1985. Their research indicates that a parallel preattentive process can indicate the presence (or absence) of feature gradients (these correspond to unusual or unique items in the display). The identification of the particular features, however, appears to require a time-consuming serial search. In the current experiment, target-absent feature search set trials are characterized by the lack of feature differences (thus the lack of feature gradients) across the set of indexed items. A feature gradient would, however, be present in target-present feature subset trials (since the target differs in one feature from all distractors). According to Sagi and Julesz, the determination of exactly *what* difference is signalled by the feature gradient would require a serial search; in fact, the processing in target-present feature search sets appears to be serial.

In any case, a similar target-present reaction time slope is observed for both selective search over an indexed subset of display items (Experiment 3), and search when those same items appear alone in the display (Experiment 3b). Therefore, this result does not compromise the basic conclusion that indexed subsets are processed as if they are the only items in the display.

General Discussion

The results of experiments reported in this thesis support one of the claims of FINST theory: namely, the claim that the visual system has a means to index a number of spatially disparate features. It appears that visual indexes provide direct access of attentional processing to the indexed items, eliminating the need for a visual scan to access the particular locations. There are several aspects of the experimental results that are relevant to this claim.

Summary of Experimental Results

These results provide further evidence that multiple locations in the visual fi `d can be simultaneously indexed as a result of their abrupt onset (similar results are reported in a number of other studies, including those by Yantis & Johnson, 1990, and Pylyshyn & Storm, 1988). In the experiments reported in this thesis, it is *not* the case that indexes are assigned (and items selected for processing) on the basis of an enduring stimulus quality. Instead, the 'feature' that defines an object to be indexed is a temporally punctate event; namely, late onset relative to other items in the display. Thus, it is evident that all indexes must be assigned (and items selected) when the late items appear, and not at a later time.

Experiment 1 explicitly demonstrates that search among a larger number of items is speeded if a subset of items are identified as potential target locations. This effect is attributed to the indexing and subsequent selective processing of the cued items. Aside from a general slowing of responses when cued items are selectively processed (this may be due to a general cost of filtering; see Treisman, Kahneman, & Burkell, 1983), search performance for three items selected among fifteen is similar to performance when the three items appear alone.

This reaction time advantage for search over subsets of display items cannot be attributed to selective attention (on any one trial) to a *single* one of the cued items. The strongest evidence for this claim is the consistent reaction time advantage for search among feature search subsets as opposed to conjunction search subsets (first observed in Experiment 1, and replicated in all other experiments in this thesis). The difference between these two conditions is defined over the *set* of indexed items: feature subsets include homogenous distractors, while conjunction subsets include mixed distractors. In every case, each single distractor shares one feature with the target item. A single distractor, therefore, cannot constitute a feature subset or a conjunction subset. If only one of the indicated items were indexed on any trial, there would be no difference observed between the feature search subset and conjunction search subset conditions. The consistent difference demonstrated in these experiments indicates that more than one item is indexed at any time.

Further evidence supporting the assertion that multiple items are in fact indexed on any trial is provided in the results of Experiment 3. In this experiment, false targets are included among the uncued items. In displays *without* false targets, it is possible to complete a search of the entire display to verify the accuracy of a "no target" response (if the single selected item is the target, there is no need to verify the response). Correct responding could, therefore, reflect indexing of only one of the cued items, augmented by search across the entire display when the item is not a target. When displays include false targets, however, it is not possible to verify the response if a single selected item is not a target; in this event, a guessing strategy would have to be used to produce a response. The error rates observed for target-present trials are 4.4% for Experiment 1, 4.0% for Experiment 2, and 3.1% for the three-item displays in Experiment 3. If fewer than three items are indexed, error rates for Experiment 3 should be higher than those observed in Experiments 1 and 2, where target-absent responses could be confirmed by a search over the entire display (as noted earlier, it is not necessary to confirm target-present responses). In fact, error rates are lower in Experiment 3. Furthermore, there is no guessing strategy that would produce the degree of accuracy observed in this experiment, even if two (much less one) of the three items were selected on any trial. Based on the (conservative) assumption that a target included among two FINSTed items is *never* missed, the best possible guessing strategy (if two items are FINSTed from a set of three) yields an accuracy of 83.9% for the target-present trials.[20]

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[20]There are three possible ways to choose two items from among three. Considering target-present trials only, two of these three pairs will include the target item. If these two items are always identified correctly (a conservative assumption in the current context), the accuracy for this subset of trials will be 100%, resulting in a baseline correct target-present response of 2/3, or 66.7%.

Now consider the 1/3 of target-present trials in which the target was not included among the subset of two items. There are two possible ways that a 'target-present' response can be given in response to these trials. One possibility is that observers mistake one of the two non-target items for a target. A reasonable estimate of this probability is the target-absent errors for the two-item subsets reported in Experiment 3, which is 1.9%. Another possibility is that observers correctly guess that the 'missed' item was a target. There are two reasonable guessing strategies: one, based on the overall probability of target-present trials, will result in correct target-present guessed for 50% of the guessed trials; the second, based on the occurrence of target items among the un-FINSTed items (each of which

The results of Experiments 2 and 2b replicate the feature search subset advantage observed in Experiment 1, as do the results of Experiment 3. Experiments 2 and 2b indicate that the feature search subset advantage is not attenuated by increases in the dispersion of the cued subset accompanied by increases in the number of uncued items included within the spatial extent of the cued subset. Experiment 3 extends the effect to larger indexed subsets, suggesting that observers can selectively process a subset of as many as five items in a larger display. In Experiment 3, the reaction time advantage for feature search subsets increases with the number of items in the cued subset. In this respect, and many others, the effect on search performance is identical whether or not uncued distractors are included with a number of abrupt onset items that constitute a search set. Thus, it appears that observers search over the selected subset as if they were the only items in the display.

According to Experiments 2 and 2b, neither increases in the dispersion of the cued subset nor increases in the number of intervening items reduce the feature search subset advantage. Furthermore, by the results of Experiment 3, the feature search advantage increases with the size of the selected subset. Together, these results have particular implications for the processing of an indexed subset of items. According to theories of visual search (e.g, FIT: Treisman & Gelade, 1980; Guided Search: Wolfe

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is equally likely to have been the third item in the indicated subset), will result in correct target-present guesses on 8/22 (the number of target items divided by the number of un-FINSTed items) of the guessed trials. The first strategy will clearly result in the greatest proportion of correct guesses for the target-present trials.

Therefore, the best possible performance, if only two items are FINSTed, is: .667+(1/3*.019)+(1/3*.5)=.839, or 83.9%. The observed accuracy for three-item target-present trials is 96.9%, discounting the hypothesis that only two items among three are FINSTed.

et al., 1989; and a competitive interaction model proposed by Duncan & Humphreys, 1989) the advantage for the feature search arises from parallel processes assumed to be applied over the entire visual array. The demonstration of a similar feature search *subset* advantage in Experiments 2, 2b and 3 suggest that it is possible (and in fact may be necessary) for observers to apply these parallel processes selectively over the set of indexed items, rather than over the display as a whole. This suggestion arises from the fact that parallel processes applied over the entire array would provide exactly the same result for feature search and conjunction search subsets, and thus would not result in the observed feature subset advantage.

Contrary to the predictions of either a spotlight model or a zoom lens model of attention, the results of Experiments 2 and 2b indicate that the time required to process an indexed subset of items does not increase with the dispersion of the items. In fact, a general *decrease* in reaction time is observed (for at least some subjects) as the distance between the cued items increases. FINST theory assumes that visual indexes provide direct access to indexed features; thus, FINST theory proposes that the time required to access each of a set of indexed items should be independent of the dispersion of the items. It is possible that the effect of dispersion observed in Experiments 2 and 2b arises from interference in the processing (at least in the current task) of nearby FINSTs, rather than at the level of access. Under this assumption, FINST theory is compatible with the observed results; certainly, a theory of multiple visual indexes (rather than a theory of a single attentional locus) is required to account for the observed dispersion effect.

Theoretical Implications

The results of the experiments included in this thesis are compatible with the claim that indexed items behave, in many respects, as if they are the only items in the display. Given a set of indexed items, observers are capable of restricting visual search to those items alone. Furthermore, it appears that both the parallel and serial aspects of the search process can be applied selectively to the indexed items, regardless of their spatial dispersion and number (within the limit of the number of FINSTs, which is assumed to be approximately five). Finally, the time required to process indexed items does not increase as they move further apart, supporting the FINST theory assumption that FINSTs provide direct access to indexed locations, obviating the need for an analog scan to move attention between indexed locations.

These results are incompatible with both the spotlight and zoom lens theories of attention, which postulate a unitary focus of visual attention. Either of these models could account for the results, however, if they were modified to include a visual indexing mechanism. Under a modified proposal, visual indexing would underlie (in functional terms) the attentional mechanism as it is modelled in either theory. Attention would be deployed only to indexed locations, and multiple visual indexes would provide simultaneous potential direct access to a number of indexed locations throughout the display; as the only potential targets for visual attention, these items could act if they were alone in the display.

Of course, as indicated throughout the thesis, this research is not intended to test all aspects of FINST theory, many of which remain unconfirmed. Thus it may be premature to propose a hybrid model of visual attention which includes an indexing mechanism. Nonetheless, FINST theory is supported by a variety of converging evidence that is strengthened by the results presented in this thesis. It remains for further research to test other FINST theory assumptions, and eventually to determine the viability of a hybrid model of visual attention.

Suggestions for Further Research

In Experiments 2 and 2b, the observation of a reaction time decrease with increased dispersion of the indexed items is a somewhat puzzling result. Although this result does not hold for all subjects, there is a subset of subjects who show the effect, which is not eliminated when it is ensured that subjects are maintaining fixation. It is possible that this unexpected effect of dispersion is a consequence of attentional processes which are not perfectly constrained to indexed objects; that is, some (if not all) attentional processes may result in a gaussian-shaped window of activation around each FINSTed object. In fact, a gradient model of exogenously oriented visual attention is proposed by Henderson (1991) and Henderson and Macquistan (1993). Further research with the selective search paradigm could investigate the possibility of gaussian shaped activation windows around multiple FINSTed objects. Independent manipulation of the distance between FINSTed objects and the distance to the nearest object (regardless of its FINST status) could disentangle hypotheses of interference between FINSTs and interference from spatially intermediate, unFINSTed items which are facilitated by nearby FINSTs.

There are also a number of interesting and important issues, relevant to visual indexing, that are outside the domain of this series of experiments. Indexing of pre-existing (but not abrupt onset) objects in the display should be investigated, to determine if observers can voluntarily select a subset of identical items in a display, based on a cuing procedure that will not induce a FINST through bottom-up influences (e.g., central cues such as arrows pointing to the subset of objects). Various manipulations of the unselected items (e.g., manipulations of number, spatial distribution, or identity) will reveal the degree to which un-FINSTed items are successfully 'filtered out' when FINSTed items are selected for processing. Finally, investigation of the time course of selective search effects will help to determine the temporal characteristics of FINSTs. If the FINSTing process underlies peripheral cuing effects, as suggested in the introduction, then selective search performance (which is also based on FINSTs) may be expected to decline within the same time frame as the decline of facilitation in response to peripheral cues.

Appendix A:

Analysis of Variance Summary Tables for Experiment 1

Table A-1
Experiment 1: Error Analysis of Variance

Source	SS	df	MS	F	p
Cuing Condition(C)	21.13	1	21.13	.65	.447
S×C	228.38	7	32.63		
Item Numerosity(N)	45.12	1	45.12	21.60	.002
S×N	14.62	7	2.09		
Search Set Type(T)	87.78	1	87.78	19.84	.003
S×T	30.97	7	4.42		
Target Presence(P)	185.28	1	185.28	8.75	.021
S×P	148.22	7	21.17		
C×N	.03	1	.03	.00	.962
S×C×N	91.22	7	13.03		
C×T	3.13	1	3.13	.39	.550
S×C×T	55.63	7	7.95		
C×P	.50	1	.50	.05	.828
S×C×P	69.00	7	9.86		
N×T	3.13	1	3.13	.62	.457
S×N×T	35.38	7	5.05		
N×P	32.00	1	32.00	6.10	.043
S×N×P	36.75	7	5.25		
T×P	9.03	1	9.03	3.47	.105
S×T×P	18.22	7	2.60		
C×N×T	19.53	1	19.53	3.85	.090
S×C×N×T	35.47	7	5.07		
C×N×P	.03	1	.03	.00	.968
S×C×N×P	130.22	7	18.60		
C×T×P	8.00	1	8.00	1.29	.293
S×C×T×P	43.25	7	6.18		
N×T×P	32.00	1	32.00	3.61	.099
S×N×T×P	62.00	7	8.86		
C×N×T×P	5.28	1	5.28	.77	.410
S×C×N×T×P	48.22	7	6.89		

Table A-2
Experiment 1: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Cuing Condition(C)	62790.82	1	62790.82	8.84	.021
S×C	49723.99	7	7103.43		
Item Numerosity(N)	181277.26	1	181277.26	64.65	.001
S×N	19628.05	7	2804.01		
Search Set Type(T)	256059.57	1	256059.57	40.22	.001
S×T	44564.24	7	6366.32		
Target Presence(P)	35344.76	1	35344.76	13.17	.008
S×P	18791.05	7	2684.44		
C×N	28590.38	1	28590.38	4.65	.068
S×C×N	43080.18	7	6154.31		
C×T	85749.76	1	85749.76	17.48	.004
S×C×T	34334.80	7	4904.97		
C×P	1617.38	1	1617.38	3.22	.116
S×C×P	3514.68	7	502.10		
N×T	23517.38	1	23517.38	5.19	.057
S×N×T	31747.18	7	4535.31		
N×P	11193.82	1	11193.82	7.28	.031
S×N×P	10761.74	7	1537.39		
T×P	6569.45	1	6569.45	4.54	.071
S×T×P	10136.12	7	1448.02		
C×N×T	29010.38	1	29010.38	8.39	.023
S×C×N×T	24210.93	7	3458.70		
C×N×P	285.01	1	285.01	.11	.753
S×C×N×P	18647.80	7	2663.97		
C×T×P	122.07	1	122.07	.41	.544
S×C×T×P	2101.24	7	300.18		
N×T×P	4266.57	1	4266.57	3.68	.097
S×N×T×P	8113.74	7	1159.11		
C×N×T×P	388.51	1	388.51	.42	.536
S×C×N×T×P	6415.55	7	916.51		

Appendix B:

Analysis of Variance Summary Tables for Experiment 2

Table B-1
Experiment 2: Percent Error Analysis of Variance

Source	SS	df	MS	F	p
Target Presence(P)	3.45	1	3.45	.14	.718
S×P	170.74	7	24.39		
Search Set Type(T)	187.70	1	187.70	7.68	.028
S×T	170.99	7	24.43		
Dispersion(D)	75.21	3	25.07	1.17	.345
S×D	450.35	21	21.45		
P×T	150.95	1	150.95	11.91	.011
S×P×T	88.74	7	12.68		
P×D	82.34	3	27.45	1.40	.271
S×P×D	411.73	21	19.61		
T×D	35.84	3	11.95	.84	.487
S×T×D	298.73	21	14.23		
P×T×D	45.59	3	15.20	.81	.504
S×P×T×D	394.98	21	18.81		

Table B-2
Experiment 2: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Target Presence(P)	50601.76	1	50601.76	14.00	.007
S×P	25305.80	7	3615.11		
Search Set Type(T)	40363.51	1	40363.51	14.27	.007
S×T	19798.55	7	2828.36		
Dispersion(D)	19352.27	3	6450.76	4.56	.013
S×D	29738.16	21	1416.10		
P×T	10170.95	1	10170.95	6.32	.040
S×P×T	11259.87	7	1608.55		
P×D	5133.09	3	1711.03	1.42	.264
S×P×D	25219.10	21	1200.91		
T×D	5861.71	3	1953.90	1.40	.271
S×T×D	29328.98	21	1396.62		
P×T×D	474.27	3	158.09	.31	.815
S×P×T×D	10551.66	21	502.46		

Table B-3
Subject CR: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	228118.9	5	45623.8	4.98	.001
Target Presence(P)	31.5	1	31.5	.00	.953
Search Set Type(T)	171072.7	1	171072.7	18.66	.001
Dispersion(D)	53843.0	3	17947.7	1.96	.121
2-Way Interactions	56275	7	8039.29	.88	.525
P×T	1089.6	1	1089.6	.12	.731
P×D	44009.0	3	14669.7	1.60	.190
T×D	11455.5	3	3818.5	.42	.741
3-Way Interactions	28392.0	3	9464.0	1.03	.379
P×T×D	28392.0	3	9464.0	1.03	.379
Within Groups	2346[illegible]4.0	256	9167.4		

Table B-4
Subject PP: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	232291.7	5	46458.3	2.16	.059
Target Presence(P)	163257.2	1	163257.2	7.60	.006
Search Set Type(T)	14556.6	1	14556.6	.68	.411
Dispersion(D)	50331.1	3	16777.0	.78	.506
2-Way Interactions	109225.0	7	15603.6	.73	.650
P×T	31069.9	1	31069.9	1.45	.230
P×D	54871.7	3	18290.6	.85	.467
T×D	21940.4	3	7313.5	.34	.796
3-Way Interactions	37923.8	3	12641.3	.59	.623
P×T×D	37923.8	3	12641.3	.59	.623
Within Groups	5585974.9	260	21484.5		

Table B-5
Subject BA: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	308168.9	5	61633.8	6.07	.001
Target Presence(P)	131613.4	1	131613.4	12.97	.001
Search Set Type(T)	173288.2	1	173188.2	17.06	.001
Dispersion(D)	11850.5	3	3950.2	.39	.761
2-Way Interactions	158336.8	7	22619.5	2.23	.032
P×T	77526.6	1	77526.6	7.64	.006
P×D	76270.4	3	25423.5	2.51	.060
T×D	3967.4	3	1322.5	.13	.942
3-Way Interactions	22566.1	3	7522.0	.74	.528
P×T×D	22566.1	3	7522.0	.74	.528
Within Groups	2659236.9	262	10149.8		

Table B-6
Subject JB: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	146773.1	5	29354.6	3.58	.004
Target Presence(P)	11830.4	1	11830.4	1.44	.231
Search Set Type(T)	115709.3	1	115709.3	14.12	.001
Dispersion(D)	21184.2	3	21184.2	.86	.461
2-Way Interactions	206846.8	7	29549.5	3.61	.001
P×T	133390.8	1	13390.8	16.28	.001
P×D	44171.1	3	14723.7	1.80	.148
T×D	33603.6	3	11201.2	1.37	.253
3-Way Interactions	1406.4	3	468.8	.06	.982
P×T×D	1406.4	3	468.8	.06	.982
Within Groups	2064668.5	252	8193.12		

Table B-7
Subject JG: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	469451.9	5	93890.4	2.67	.023
Target Presence(P)	8478.0	1	8478.0	.24	.624
Search Set Type(T)	15039.9	1	15031.9	.43	.514
Dispersion(D)	438178.8	3	146059.6	4.15	.007
2-Way Interactions	442742.9	7	63249.0	1.80	.089
P×T	7045.2	1	7045.2	.20	.655
P×D	208639.4	3	69546.5	1.98	.118
T×D	234190.4	3	78063.5	2.22	.087
3-Way Interactions	42329.9	3	1410.0	.40	.753
P×T×D	42329.9	3	1410.0	.40	.753
Within Groups	8273357.0	235	35205.8		

Table B-8
Subject RE: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	220806.8	5	44161.4	4.32	.001
Target Presence(P)	62249.7	1	62249.7	6.01	.014
Search Set Type(T)	60324.8	1	60324.8	5.91	.016
Dispersion(D)	92201.2	3	30733.7	3.01	.031
2-Way Interactions	116868.8	7	16695.5	1.64	.126
P×T	14.0	1	14.0	.00	.971
P×D	59457.5	3	19819.2	1.94	.124
T×D	53422.9	3	17807.6	1.74	.159
3-Way Interactions	3120.8	3	1040.3	.10	.959
P×T×D	3210.8	3	1040.3	.10	.959
Within Groups	2400124.0	235	10213.3		

Table B-9
Subject BF: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	842828.2	5	168565.6	12.49	.001
Target Presence(P)	344101.5	1	344101.5	25.49	.001
Search Set Type(T)	386540.5	1	386540.5	28.63	.001
Dispersion(D)	115529.6	3	38509.9	2.85	.038
2-Way Interactions	75711.8	7	10816.0	.80	.587
P×T	25956.3	1	25956.3	1.92	.167
P×D	26478.5	3	8826.2	.65	.581
T×D	23802.8	3	7934.3	.59	.624
3-Way Interactions	49285.3	3	16428.4	1.22	.304
P×T×D	49285.3	3	16428.4	1.22	.304
Within Groups	3456507.2	256	13502.0		

Table B-10
Subject MH: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	841846.0	5	168369.2	9.40	.001
Target Presence(P)	605085.2	1	685085.2	33.77	.001
Search Set Type(T)	88663.5	1	88663.5	4.95	.027
Dispersion(D)	154706.9	3	51569.0	2.88	.037
2-Way Interactions	70191.1	7	10027.3	.56	.788
P×T	464.2	1	464.2	.03	.872
P×D	48672.0	3	16224.0	.91	.439
T×D	22293.1	3	7431.0	.42	.743
3-Way Interactions	22844.8	3	7614.9	.43	.735
P×T×D	22844.8	3	7614.9	.43	.735
Within Groups	4569448.3	255	17919.4		

Appendix C:

Analysis of Variance Summary Tables for Experiment 2b

Table C-1
Experiment 2b: Proportion Rejected Analysis of Variance for Subject JB

Source	SS	df	MS	F	p
Main Effects	.050	5	.010	.14	.984
Target Presence(P)	.000	1	.000	.00	1.000
Search Set Type(T)	.025	1	.025	.34	.559
Dispersion(D)	.025	3	.008	.11	.952
2-Way Interactions	.142	7	.020	.28	.963
P×T	.000	1	.000	.00	1.000
P×D	.083	3	.028	.38	.768
T×D	.058	3	.019	.27	.851
3-Way Interactions	.317	3	.106	1.44	.230
P×T×D	.317	3	.106	1.44	.230
Within Groups	104.467	1424	.073		

Table C-2
Experiment 2b: Proportion Rejected Analysis of Variance for Subject RE

Source	SS	df	MS	F	p
Main Effects	.323	5	.065	.58	.716
Target Presence(P)	.063	1	.063	.57	.452
Search Set Type(T)	.113	1	.113	1.01	.315
Dispersion(D)	.147	3	.049	.44	.725
2-Way Interactions	.294	7	.042	.38	.917
P×T	.037	1	.037	.33	.567
P×D	.012	3	.004	.04	.991
T×D	.245	3	.082	.73	.533
3-Way Interactions	.056	3	.019	.17	.918
P×T×D	.056	3	.019	.17	.918
Within Groups	159.070	1424	.112		

Table C-3
Experiment 2b: Percent Error Analysis of Variance for Subject JB

Source	SS	df	MS	F	p
Main Effects	.610	5	.122	3.02	.010
Target Presence(P)	.302	1	.302	7.47	.006
Search Set Type(T)	.264	1	.264	6.54	.011
Dispersion(D)	.046	3	.015	.38	.770
2-Way Interactions	.220	7	.031	.78	.608
P×T	.014	1	.014	.34	.561
P×D	.124	3	.041	1.03	.380
T×D	.080	3	.027	.66	.574
3-Way Interactions	.151	3	.050	1.24	.293
P×T×D	.151	3	.050	1.24	.293
Within Groups	50.725	1255	.040		

Table C-4
Experiment 2b: Percent Error Analysis of Variance for Subject RE

Source	SS	df	MS	F	p
Main Effects	2.467	5	.493	5.75	.001
Target Presence(P)	1.507	1	1.507	17.56	.001
Search Set Type(T)	.621	1	.621	7.24	.007
Dispersion(D)	.306	3	.102	1.19	.313
2-Way Interactions	1.637	7	.234	2.73	.008
P×T	.063	1	.063	.74	.390
P×D	1.237	3	.412	4.81	.002
T×D	.349	3	.116	1.36	.255
3-Way Interactions	.105	3	.035	.41	.748
P×T×D	.105	3	.035	.41	.748
Within Groups	97.735	1139	.086		

Table C-5
Experiment 2b: Reaction Time Analysis of Variance for Subject JB

Source	SS	df	MS	F	p
Main Effects	1265866.8	5	253173.2	40.90	.001
Target Presence(P)	286096.0	1	286096.0	46.22	.001
Search Set Type(T)	972111.6	1	972111.6	157.10	.001
Dispersion(D)	13662.1	3	4554.0	.73	.531
2-Way Interactions	405230.8	7	57890.1	9.35	.001
P×T	370485.2	1	370485.2	59.86	.001
P×D	27852.1	3	9284.0	1.50	.213
T×D	8731.1	3	2910.4	.47	.703
3-Way Interactions	12021.4	3	4007.1	.64	.585
P×T×D	12021.4	3	4007.1	.64	.585
Within Groups	7433463.5	1201	6189.4		

Table C-6
Experiment 2b: Reaction Time Analysis of Variance for Subject RE

Source	SS	df	MS	F	p
Main Effects	1070324.6	5	214064.9	23.43	.001
Target Presence(P)	778895.1	1	778895.1	85.24	.001
Search Set Type(T)	216941.2	1	216941.2	23.74	.001
Dispersion(D)	104592.1	3	34864.0	3.82	.010
2-Way Interactions	489736.7	7	69962.4	7.66	.001
P×T	287148.5	1	287148.5	31.42	.001
P×D	176044.7	3	58681.6	6.42	.001
T×D	44546.6	3	14848.9	1.63	.182
3-Way Interactions	53183.5	3	17727.8	1.94	.121
P×T×D	52183.5	3	17727.8	1.94	.121
Within Groups	9375327.4	1026	9137.7		

Appendix D:

Analysis of Variance Summary Tables for Experiment 3

Table D-1
Experiment 3: Error Analysis of Variance

Source	SS	df	MS	F	p
Number of Cues(C)	1626.46	3	524.15	15.82	<.05*
S×C	308.45	9	34.27		
Search Set Type(T)	122.07	1	122.07	11.01	.045
S×T	33.27	3	11.09		
Target Presence(P)	155.32	1	155.32	24.02	.016
S×P	19.40	3	6.47		
Level of Practice(Pr)	82.88	1	82.88	17.19	.025
S×Pr	14.46	3	4.82		
C×T	124.96	3	541.65	5.47	.020
S×C×T	68.57	9	7.62		
C×P	146.46	3	48.82	16.16	.001
S×C×P	27.20	9	3.02		
C×Pr	52.02	3	17.34	.88	.487
S×C×Pr	177.51	9	19.72		
T×P	6.57	1	6.57	.66	.475
S×T×P	29.77	3	9.92		
T×Pr	6.57	1	6.57	.86	.422
S×T×Pr	22.90	3	7.63		
P×Pr	.01	1	.01	.00	.967
S×P×Pr	15.86	3	5.29		
C×T×P	30.59	3	10.20	3.34	>.25*
S×C×T×P	27.45	9	3.05		
C×T×Pr	1.96	3	.65	.10	>.25*
S×C×T×Pr	57.45	9	6.38		
C×P×Pr	12.65	3	4.22	.55	.660
S×C×P×Pr	68.88	9	7.65		
T×P×Pr	.95	1	.95	.06	.819
S×T×P×Pr	45.27	3	15.09		
C×T×P×Pr	23.21	3	7.74	.94	.460
S×C×T×P×Pr	73.95	9	8.22		

* Significance evaluated at 1 and n-1 (3) degrees of freedom, to adjust for violation of sphericity according to the Geisser Greenhouse conservative F test (Kirk, 1982)

Table D-2
Experiment 3: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Number of Cues(C)	156347.03	3	52115.68	21.97	.001
S×C	21353.78	9	52115.68		
Search Set Type(T)	136111.53	1	13611.53	31.99	.011
S×T	15981.78	3	5327.26		
Target Presence(P)	42122.53	1	42122.53	11.94	.041
S×P	10581.66	3	3527.22		
Level of Practice(Pr)	42267.78	1	42267.78	6.74	.081
S×Pr	18806.03	3	6268.68		
C×T	50834.03	3	16944.68	13.54	.001
S×C×T	11267.03	9	1251.89		
C×P	2203.41	3	734.47	4.18	.041
S×C×P	1580.16	9	734.47		
C×Pr	2621.03	3	873.68	2.51	.124
S×C×Pr	3131.41	9	347.93		
T×P	20351.53	1	20351.53	66.95	.004
S×T×P	911.91	3	303.97		
T×Pr	344.53	1	344.53	.19	.689
S×T×Pr	5311.03	3	1770.34		
P×Pr	69.03	1	69.03	.12	.751
S×P×Pr	1709.03	3	569.68		
C×T×P	7961.91	3	2653.97	19.06	.001
S×C×T×P	733.02	9	122.17		
C×T×Pr	515.78	1	258.78	.28	.636
S×C×T×Pr	3680.41	9	408.93		
C×P×Pr	539.41	3	179.80	1.31	>.25*
S×C×P×Pr	1186.85	9	197.81		
T×P×Pr	258.78	1	258.78	.28	.636
S×T×P×Pr	2810.03	3	936.68		
C×T×P×Pr	597.16	3	199.05	.64	.609
S×C×T×P×Pr	2808.78	9	312.09		

* Significance evaluated at 1 and n-1 (3) degrees of freedom, to adjust for violation of sphericity according to the Geisser Greenhouse conservative F test (Kirk, 1982)

Table D-3
Subject JB: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	14785828	6	2464304.67	195.00	.001
Number of Cues(C)	8287250	3	2762416.52	218.58	.001
Search Set Type(T)	5584845	1	5584844.95	441.92	.001
Target Presence(P)	69321	1	69320.95	5.49	.019
Level of Practice(Pr)	1044100	1	104099.53	82.62	.001
2-Way Interactions	3845372	12	320447.69	25.36	.001
C×T	2849696	3	949898.62	75.16	.001
C×P	60203	3	20067.57	1.59	.199
C×Pr	118761	3	39586.94	3.13	.025
T×P	733259	1	733259.42	58.02	.001
T×Pr	1420	1	1419.71	.11	.738
P×Pr	76027	1	76027.14	6.02	.014
3-Way Interactions	384297	10	38429.73	3.04	.001
C×T×P	279124	3	93041.44	7.36	.001
C×T×Pr	65931	3	21976.90	1.74	.157
C×P×Pr	14037	3	4679.08	.37	.774
T×P×Pr	29680	1	29680.13	2.35	.126
4-Way Interactions	157576	3	52525.29	4.16	.006
C×T×P×Pr	157576	3	52525.29	4.16	.006
Within Groups	37837497	2994	12637.78		

Table D-4
Subject BA: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	3044330	6	507388.39	68.34	.001
Number of Cues(C)	1468176	3	489391.84	65.92	.001
Search Set Type(T)	875606	1	875606.68	117.94	.001
Target Presence(P)	607246	1	607245.68	81.79	.001
Level of Practice(Pr)	157825	1	157824.74	21.26	.001
2-Way Interactions	786507	12	65542.23	8.83	.001
C×T	421000	3	140333.40	18.90	.001
C×P	55665	3	18555.12	2.50	.058
C×Pr	94890	3	31629.95	4.26	.005
T×P	185713	1	185713.39	25.01	.001
T×Pr	14818	1	14817.71	2.00	.158
P×Pr	16354	1	16354.00	2.20	.138
3-Way Interactions	258823	10	25882.34	3.49	.001
C×T×P	206888	3	68962.83	9.29	.001
C×T×Pr	50852	3	16950.72	2.28	.077
C×P×Pr	1383	3	461.01	.06	.980
T×P×Pr	339	1	339.37	.05	.831
4-Way Interactions	5339	3	1799.78	.24	.869
C×T×P×Pr	5339	3	1779.78	.24	.869
Within Groups	17781172	2395	7424.29		

Table D-5
Subject FM: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	13249070	6	2208178.34	110.28	.001
Number of Cues(C)	1918372	3	639457.35	31.94	.001
Search Set Type(T)	4611311	1	4611310.96	230.29	.001
Target Presence(P)	2684305	1	2684305.38	134.06	.001
Level of Practice(Pr)	4225615	1	4225615.04	211.03	.001
2-Way Interactions	3173463	12	264455.25	13.21	.001
C×T	1742581	3	580860.41	29.01	.001
C×P	167414	3	55804.73	2.79	.039
C×Pr	236237	3	78745.67	3.93	.008
T×P	582662	1	582662.27	29.10	.001
T×Pr	438330	1	438329.65	21.89	.001
P×Pr	36111	1	36110.87	1.80	.179
3-Way Interactions	557656	10	55765.58	2.79	.002
C×T×P	184305	3	61434.86	3.07	.027
C×T×Pr	180872	3	60290.77	3.01	.029
C×P×Pr	96388	3	32129.46	1.61	.186
T×P×Pr	98548	1	98548.45	4.93	.027
4-Way Interactions	95792	3	61930.65	1.60	.189
C×T×P×Pr	95792	3	61930.65	1.6	.189
Within Groups	59630434	2978	20023.65		

Table D-6
Subject JL: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Main Effects	7847300	6	1307883.41	252.58	.001
Number of Cues(C)	4334383	3	1444794.40	279.02	.001
Search Set Type(T)	2121158	1	2121157.57	409.64	.001
Target Presence(P)	1274347	1	1274346.88	246.10	.001
Level of Practice(Pr)	176502	1	176502.47	34.09	.001
2-Way Interactions	1188686	12	99057.18	19.13	.001
C×T	729270	3	243090.15	46.95	.001
C×P	17.59	3	5686.50	1.10	.549
C×Pr	65400	3	21800.17	4.21	.006
T×P	308819	1	308819.02	56.64	.001
T×Pr	23788	1	23787.80	4.59	.032
P×Pr	27290	1	27290.29	5.27	.022
3-Way Interactions	434726	10	43472.57	8.40	.001
C×T×P	145440	3	48480.05	9.36	.001
C×T×Pr	77957	3	25985.54	5.02	.002
C×P×Pr	44278	3	14759.24	2.85	.036
T×P×Pr	173720	1	173719.75	33.55	.001
4-Way Interactions	60623	3	20207.60	3.90	.009
C×T×P×Pr	60623	3	20207.60	3.90	.009
Within Groups	16212578	3131	5178.08		

Appendix E:

Analysis of Variance Summary Tables for Experiment 3b

Table E-1
Experiment 3b: Error Analysis of Variance

Source	SS	df	MS	F	p
Number of Items(I)	45.42	3	15.14	3.48	.064
S×I	39.14	9	4.35		
Search Set Type(T)	19.14	1	19.14	1.96	.256
S×T	29.30	3	9.77		
Target Presence(P)	165.77	1	165.77	3.31	.167
S×P	150.42	3	50.14		
I×T	9.05	3	3.02	.24	.857
S×I×T	113.77	9	12.64		
I×P	33.42	3	11.14	1.42	.300
S×I×P	70.64	9	7.85		
T×P	.77	1	.77	.40	.570
S×T×P	5.67	3	1.89		
I×T×P	48.42	3	16.14	1.11	.396
S×I×T×P	131.39	9	14.60		

Table E-2
Experiment 3b: Reaction Time Analysis of Variance

Source	SS	df	MS	F	p
Number of Items(I)	50728.81	3	16909.60	38.38	.001
S×I	3964.81	9	440.53		
Search Set Type(T)	66951.56	1	66951.56	57.35	.005
S×T	3502.06	3	1167.35		
Target Presence(P)	12544.00	1	12544.00	11.18	.044
S×P	3365.38	3	1121.79		
I×T	12955.56	3	4318.52	13.13	.001
S×I×T	2960.81	9	328.98		
I×P	1245.13	3	415.04	1.03	.426
S×I×P	3638.50	9	404.28		
T×P	1600.00	1	1600.00	2.28	.228
S×T×P	2101.62	3	700.54		
I×T×P	2942.88	3	980.96	3.26	.074
S×I×T×P	2711.50	9	301.28		

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