Searching through subsets:

A test of the Visual Indexing Hypothesis

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Abstract

This paper presents three experiments investigating the claim that the visual system utilizes a primitive indexing mechanism (sometimes called FINSTS; Pylyshyn, 1989) to make non-contiguous features directly accessible for further visual processing. This claim is investigated using a variant of the conjunction search task in which subjects search among a subset of the items in a conjunction search display for targets defined by a conjunction of colour and orientation. The members of the subset were identified by virtue of the late onset of the objects' place-holders. The cued subset was manipulated to include either homogenous distractors or mixed distractors. Observers were able to select a subset of three items from among fifteen for further processing (Experiment 1); furthermore, a reaction time advantage for homogenous subsets over mixed subsets was observed, indicating that more than one of the subset is selected for further specialized processing. The homogeneous subset advantage held for subsets of two to five items (Experiment 2), and the time required to process the cued subset did not increase with increased dispersion of the items (Experiment 3). These results support the basic claim of the indexing theory: The claim that multiple visual indexes are used in selecting objects for visual processing.

This paper is concerned with exploring certain visual phenomena (particularly involving visual search) which suggest that some aspect, or perhaps some stage, of visual attention involves parallel access to several disparate locations in a visual display. Most theoretical accounts of attention hold that visual attention is unitary in the sense that it is confined to one contiguous region in space. It is widely agreed that the size (e.g., Hughes and Zimba, 1985; LaBerge, 1983), and 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 are, however, generally viewed as the limits of flexibility of the attentional process. In particular, both the spotlight model (e.g., LaBerge, 1983; Posner, Snyder and Davidson, 1980) and the zoom lens model (e.g., Eriksen and St. James, 1986; Eriksen and Yeh, 1985) hold that attentional facilitation cannot be split across multiple locations.

Although there is a large body of research arguing for a single focus of visual attention (e.g., Kiefer and Siple, 1987; Posner et al., 1980), this result is not unequivocal, and there are a number of studies which support the notion that at least some attentional processes can be simultaneously applied over multiple spatially disparate locations (Shaw and Shaw, 1977; Egly and Homa, 1984). Driver and Baylis (1989) provide evidence that attention can be assigned specifically to the individual components of perceptual groups, even when those components are spatially dispersed and interspersed with other non-attended items (but see Kramer, Tham, and Yeh, 1991, for a failure to replicate this result). The results of Juola, Bouwhuis, Cooper, and Warner (1991) suggest 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. Castiello and Umiltà

(1992) demonstrate that observers have independent control over the area of attentional facilitation in two spatially disparate locations. Kramer and Hahn (1995) show that attention can be assigned to multiple non-contiguous locations unless intervening items are abruptly onset. If the intervening items appear without abrupt onset, they do not receive attentional processing. These results suggest that at least some attentional processes can be applied simultaneously to multiple spatially disparate locations.

One approach to accommodating such apparent multiple-locus attention results is provided by the theory of visual indexing (Pylyshyn, 1989; Pylyshyn, Burkell, Fisher, Sears, Schmidt and Trick, 1994; Pylyshyn and Storm, 1988). In that theory the process of attending to particular places or objects in the visual field is divided into at least two stages. In the first (classically "preattentive") stage, a small number of salient objects or features in the visual field are indexed using a mechanism that, for purely historical reasons, has become known as a FINST.

Visual indexes are not proposed as an alternative to the idea of a locus of focused attention. Instead, they are intended as a mechanism which mediates the engagement of visual attention, providing the means by which all subsequent attentional processes are allocated. According to the theory, indexes provide a mechanism for binding the arguments of visual routines (Ullman 1984). For example, indexes bind the arguments of routines which move focal attention or which evaluate properties of certain salient objects (including relational properties such as "collinear") to the objects to which they apply. Thus, FINST theory is entirely compatible with a hybrid model of attentional processing in which the FINST mechanism indexes 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.

According to the indexing hypothesis, a small number of items undergoing a salient change such as a sudden onset (e.g., Jonides and Yantis, 1988; Remington, Johnston and Yantis, 1992) or substantial shape change (e.g., Miller, 1989; Theeuwes, 1991) are automatically indexed (note that less salient changes, such as isoluminant colour change (Burkell, 1986) do not attract indexes). Indexed items are then directly accessible in "potentially parallel" fashion, so that they can be subsequently processed just as a set of simultaneously presented items can be visually processed -- i.e., in series or in parallel depending on the task. In addition, because the items so indexed can be accessed directly through the index, there is no need to search for them by scanning over empty regions of the display. This leads to the strong prediction that a subset of elements in a display can be indexed and thereby functionally extracted from the display and processed without regard to their physical dispersion or to the nature of the elements at un-indexed locations.

Direct evidence for multiple indexes arises from the multiple target tracking task (Pylyshyn and Storm, 1988) and the investigation of the facilitation of multiple abrupt onset items (Yantis and Johnson, 1990). In the multiple target tracking task, observers are asked to track a number of independently moving items selected from among a larger subset of identical items. Research has shown that up to five independently moving objects can be simultaneously tracked and that this ability cannot be explained in terms of a serial-sampling process (Pylyshyn and Storm, 1988) or an expanded `zoom-lens' zone of attention (Sears and Pylyshyn, in press) Yantis and his colleagues have investigated the visual processing of abrupt onset items in a search task, showing consistent reaction time advantages for multiple abrupt onset targets (e.g., Jonides and Yantis, 1988; Yantis and Johnson, 1990). Yantis and Johnson attribute this result to `attentional priority tags' which are assigned to abrupt onset items. These attentional priority tags appear to function much like indexes, facilitating the processing of items to which they are assigned. According to the results of Yantis and Johnson (1990), approximately four abrupt onset items in a single display receive priority processing (note, however, that Yantis and Jones, 1991, suggest that it is the duration of attentional tags, and not the number, which is limited). This is very close in number to the five objects that subjects are able to independently track, and also close to the number of objects that observers can subitize, a task that also relies on indexes (Trick and Pylyshyn, 1993, 1994). These independent sources of evidence suggest that four or five indexes, each supporting direct attentional access to a different place in the visual array, are available to the visual system.

The experiments presented in this paper investigate the fundamental claim of the FINST theory: the claim that the visual system has a means to make a set of non-contiguous features directly accessible for further visual processing. This theory hypothesizes a mechanism whereby a number of independent places can be indexed so attention can be directed to those places without the necessity of first carrying out a visual scan-and-search. Consequently, if a subset of items in a visual search task is indexed, search can be confined to those items and performance should be as though the indexed items are virtually the only ones in the display. Moreover, since attention can be switched to the indexed items without first searching for them, performance should be independent of the spatial location of the indexed items (i.e. their spatial dispersion). Experiments 1, 2 and 2a investigate the claim of the separability of cued items from the rest of the display while Experiment 3 investigates the role of spatial dispersion of the cued items.

In these experiments, abrupt onset of a subset of stimuli was used to direct the assignment of indexes to those particular items. In the absence of an abrupt onset subset, it is assumed that indexes are assigned to a random subset of the items in the display. In either case, the hypothesis assumes that search processes are applied over the indexed items. If the target is not constrained to appear among the indexed subset, indexes are reassigned to new items after the initial set has been searched, until the target is detected or all items in the display have been examined.

Experiment 1: Searching Cued Subsets

The first three experiments (Experiments 1, 2 and 2a) address the question of whether a subset of items in a search task can be separated, using indexes induced by abrupt-onset cues, and subsequently searched without interference from the un-indexed items. There is evidence that stimulus properties can lead to separable subsets in a search task (e.g., colour: Green and Anderson, 1956, and Friedman-Hill and Wolfe, 1995; form: Egeth, Virzi, and Garbart, 1984; motion: McLeod, Driver and Crisp, 1988; stereo disparity: Nakayama and Silverman, 1986). In every case, the stimulus properties that support separation endure for the entire time of the task; thus, for example, items that differ in colour maintain this difference during the entire task, and items that differ in stereo disparity remain on different depth planes for the duration of the display. The current studies expand these results by: 1) using time of onset to separate the cued from uncued sets; 2) precuing with location markers only, and later presenting identifying information for both cued and uncued items simultaneously; and 3) examining the application of feature and conjunction search processes over the identified subset.

A particularly discerning test of the effectiveness of indexing to separate a subset of items can be obtained by using a variant of the conjunction search paradigm (Treisman and Gelade, 1980) which can be termed subset search (Friedman-Hill and Wolfe, 1995). In this procedure, subjects are induced to search over a subset of cued items from a larger display including both cued and uncued items. Suppose we arrange for the entire stimulus display (uncued as well as cued items) to constitute a conjunction set (mixed distractors) and then manipulate the cued subset to be either a feature set (homogeneous distractors) or a conjunction set (mixed distractors). In that case the property of being a feature-search task as opposed to a conjunction-search task is one that applies to the cued subset alone; search over the entire display is, in every case, a conjunction-search task. Moreover, the property of being a feature-search or conjunction-search task applies to the entire cued subset. A strategy that did not treat the subset as a whole, for example a local strategy of comparing each item in the subset independently against the given search target would not distinguish the two types of tasks. Consequently, any differences found between feature-subset search and conjunction-subset search tasks implies that the entire cued subset is selected and at some stage enters into further processing as a group. The selection itself might be done in parallel, although the comparisons need not be a purely parallel process. All that can be concluded from a difference between the search pattern for feature-subsets and conjunction-subsets is that in the search properties of the subset as a whole are taken into account, so the entire subset must be accessible at some stage. This will be discussed in somewhat more detail when the results are considered below.

The method adopted in the present studies involves the use of place markers to indicate where each of the visual objects was to appear in the display. To induce subset-indexing, the place holders for the search subset appeared suddenly at least one second after the ones for the non-search objects had already been presented. Previous research investigating search for conjunction targets has demonstrated that single exogenous cues (such as abrupt onset) can benefit the perception of feature conjunctions at the cued location (Briand and Klein, 1987; Treisman and Schmidt, 1982), presumably through attentional facilitation at the location of the cue. The effect of multiple cues has not been investigated in a conjunction search task. In a different search paradigm, however, Yantis and Johnson (1990) and Yantis and Jones (1991) showed that attentional benefits accrue to multiple abrupt onset items in a display, supporting the expectation that similar benefits might be observed in search for conjunction targets among a subset of items.

The present study compares visual search in cued and uncued displays of three or fifteen items, contrasting search over feature sets (homogenous distractors) with search over conjunction sets (mixed distractors).

Method

Subjects. The data from eight subjects are reported for Experiment 1. [2] The subjects ranged in age from 22 to 36 years, and each had normal or corrected to normal vision. Each subject had one full session of practice (data from these sessions are not reported), followed by one experimental session. Subjects were paid $10.00 for each session of the experiment, including the practice session.

Apparatus and Stimuli. The experiment was 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 and record the identity of each button pressed.

The items in each display occupied a subset of the thirty-six possible display positions. These positions are arranged on three concentric hexagons, centred at fixation. Potential target positions included each of the vertices of the three hexagons (numbering 18 in total), the midpoints of each edge of the middle hexagon (numbering 6), and two equally spaced points on each edge of the outermost hexagon (numbering 12). Figure 1 presents the matrix of possible display positions.

Insert Figure 1 about here.

From a viewing distance of 100 cm, each object subtended a visual angle of 0.7° (vertical) by 0.4 degrees (horizontal). The minimum distance between contours of adjacent objects was 0.92 degrees. The maximum extent of the display was 10.4 degrees (in the vertical direction) by 10.6 degrees (in the horizontal direction). The maximum distance of a target object from fixation was 5.3 degrees, and the minimum distance of a target object from fixation was 0.92 degrees.

The objects in each search display were coloured diagonal lines. There were two possible orientations (+45 degrees and -45 degrees), and two possible colours (red and green). Target items were chosen randomly for each subject from the set of four possible targets (two colours by two orientations). The choice of target item defined two distractor types, one sharing orientation (but not colour) with the target, and the other sharing colour (but not orientation) with the target.

Prior to the presentation of the search display, the position of each object was marked by a place holder. Place holders were grey in colour and X-shaped, consisting of two equal-length diagonal bars, one at +45 degrees and one at -45 degrees. Using a modification of the no-onset presentation technique (Todd and Van Gelder, 1979), each placeholder then lost one of its diagonal bars, and the remaining bar changed colour to either red or green. The three colours used in the display (red, green and grey) were matched as closely as possible in luminance using the minimal flicker technique (Boynton and Kaiser, 1978). The combination of the no-onset stimulus presentation technique and the luminance matching minimized the transitions associated with the onset of the stimulus display, thus minimizing additional transients in the display, and helping to ensure that indexes assigned to late-appearing items were not displaced by later visual events occurring in the display.

Each trial proceeded as follows. The beginning of the trial was signalled by a warning tone. After a delay of 500 msec, the place holders marking uncued items (if any were present) were displayed. A further delay of 1000 msec occurred before the placeholders marking the cued subset appeared. The entire set of placeholders remained on the screen for 100 msec, at which time each placeholder lost one diagonal line and changed colour to become either red or green. This changed display constituted the search display, which remained on the screen until the subject responded. Figure 2 presents a typical display sequence.

Insert Figure 2 about here.

Four factors were manipulated in the experiment: item numerosity (3 items, 15 items); number of cues (0 cues, 3 cues); search set type (feature set, conjunction set); and target condition (present, absent). The factorial combination resulted in 16 trial types.

Each display included either three or fifteen objects. Either 0 or 3 items were cued on each trial (note that, for 3-item cued displays, this means that all items were cued). In 3-cue displays, targets were constrained to appear among the cued items. Thus, for 3-cued trials, the cued items constitute the search set or the set of items among which a target could appear. In 0-cue displays, a target could replace any of the placeholders. For these displays, the entire set of items constitute the search set.

The items included in the search set were manipulated to constitute either a feature set (homogeneous distractors) or a conjunction set (mixed distractors). The particular distractor included in the feature sets was chosen randomly from the two possible distractors (one matching the target in colour, the other matching the target in orientation). Uncued distractors (present only in 15-item 3-cue displays) always constituted a mixed set [3].

With a single exception, each of the display items occupied a location randomly selected from the set of 36 potential display locations. 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 8 target-present trial types, the target appeared once in each of the 36 display positions. For the target-absent conditions, the target was replaced with an appropriate distractor, maintaining distractor homogeneity for the feature-search trials. This resulted in a total of 576 experimental trials (sixteen trial types, as described above, with 36 trials per type).

The 0-cue displays in this experiment exactly match the traditional conjunction search paradigm (e.g., Treisman and Gelade, 1980). The 3-cue, 15-item displays are true `subset search' displays, where observers search among a subset of all objects present in the display. The 3-item, 3-cue displays involve search over a set of three late-appearing items without accompanying uncued distractors. This condition provides a direct comparison to search in the 15-item, 3-cue displays.

Procedure. Subjects were seated in a dimly-lit room, 100 cm from the display screen. Subjects were 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. One of four possible targets (two colours by two orientations) was selected 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.

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 maintain fixation throughout the trial. 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.

Trials were blocked by cuing condition (0 cues, 3 cues), with the order of cuing condition determined randomly for each subject. Within each cuing condition, trials were blocked by item numerosity (3 items, 15 items; 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 type (feature, conjunction; 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.

Specific instructions were given before the practice trials preceding changes of item numerosity and/or cuing condition. These instructions identified the number of items that would appear in each display and described the cuing condition for the upcoming trials. The search type manipulation was not described to subjects. 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.

Results

Errors were defined either as a failure to detect a target, or a `false alarm' indicating a target when none was in fact present. 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 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; although Chun and Wolfe, 1996, raise some question about the effectiveness of this procedure). In addition, trials with reaction times greater than 2.5 standard deviations from the cell mean for each subject were discarded. These criteria resulted in the elimination of between 3.8% of trials (3 cues, 3 items, conjunction search, target-present) and 8.3% of trials (0 cues, 15 items, conjunction search, target-present).

Repeated measures analyses of variance were conducted separately for the error and reaction time data. Independent variables in the analyses were cuing condition (0 cues, 3 cues), search type (feature set, conjunction set), item numerosity (3 items, 15 items), and target condition (present, absent).

Errors averaged 3.8% over all conditions. The error analysis revealed a main effect of search type ($F_{(1,7)}=19.84$, $p<.01$): observers made more errors for conjunction searches (4.7%) than for feature searches (3.0%). 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 was also a greater tendency to miss a targets than to falsely indicate the presence of a target, as evidenced 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 was a significant interaction of item numerosity and target condition ($F_{(1,7)}=6.10$, $p<.05$). None of the pairwise contrasts within this interaction was significant (for Tukey's HSD, critical q=4.11; largest obtained q is 3.99, for the feature versus conjunction comparison within 15-item displays).

The results of the error analysis are consistent with those generally observed in visual search for conjunction targets (e.g., Treisman and Gelade, 1980). Furthermore, the lack of significant interactions involving the cuing condition indicates that the pattern of errors is similar for the 0 cue and the 3 cue conditions.

The reaction time analysis revealed a main effect of target presence ($F_{(1,7)}=13.17$, $p<.05$), along with an interaction of target presence and item numerosity ($F_{(1,7)}=7.28$, $p<.05$). Subjects were generally slower to respond to target-absent trials than target-present trials (average reaction times of 609 msec and 576 msec). The effect of target condition was greater for 15-item trials (reaction times of 656 msec and 604 msec) than for 3-item trials (reaction times of 562 msec and 548 msec).

The analysis also revealed a significant three-way interaction of search type, cuing condition and item numerosity ($F_{(1,7)}=8.39$, $p<.05$; see Figure 3), subsuming the main effects of cuing condition ($F_{(1,7)}=8.84$, $p<.05$), item numerosity ($F_{(1,7)}=64.65$, $p<.01$), and search set type ($F_{(1,7)}=40.22$, $p<.01$). The three-way interaction was explored through examination of simple two-way interactions. The effects of search type and target condition were examined separately for the 0-cue and 3-cue conditions.

Insert Figure 3 about here.

The 0-cue condition is just the standard search paradigm, as reported by Treisman and Gelade (1980). The present findings replicate the standard ones reported in the literature: i.e., a main effect of item numerosity ($F_{(1,7)}=22.27$, $p<.01$), a main effect of search 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 type indicate that reaction times were 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 were slower to respond to conjunction searches than to feature searches (average reaction times of 685 msec and 544 msec respectively for conjunction searches and feature searches). The interaction is due to the greater effect of item numerosity for conjunction searches as opposed to feature searches. The 162 msec effect of item numerosity for conjunction searches (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 searches (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). There were no effects involving target presence that reached significance.

Although the three-way interaction of item numerosity, search type, and target presence was not significant, the reaction time slopes follow the pattern generally found in the literature. Target-present and target-absent slopes for the feature condition were 3.9 ms/item and 4.1 ms/item respectively. Slopes for the conjunction condition were 11 ms/item for target-present trials, and 16.1 ms/item for target-absent trials. Thus, feature display target-present and feature display target-absent slopes were similar, and lower than the slopes observed for either target-present or target-absent displays in the conjunction condition. Slopes for the target-absent conjunction trials were higher than slopes for the target-present conjunction trials.

The slopes for the conjunction displays are lower than those observed in many search experiments [4]. It should be noted, however, that these slope estimates are based on two points only, and thus do not allow any determination of the reliability of the slope estimate. Furthermore, the standard errors of the means on which these estimates are based are quite large, ranging from 15 msec (3-item feature displays, target-present) to 51 msec (15-item conjunction displays, target-absent). Replication of this study with a larger number of display sizes would provide more reliable estimates of reaction time slopes.

It would not be surprising if the observed slopes are low under the precuing paradigm. The current study differs from traditional search experiments in one critical aspect: the location of items is marked before their identity is revealed. This early presentation of item locations may support ‘preparation’ for the search task by allowing the assignment of the 4-5 available indexes to a subset of items before the task is begun. This would speed the processing of the indexed items, and thus speed the completion of the entire task (even if the target were not within the initially indexed subset) by the early completion of one step in the search process.

The 3-cue condition involves search over 3 late-appearing items in the display. For displays of 3 items, the late-appearing subset constitute all of the items in the display. For displays of 15 items, the late-appearing subset appear with 12 mixed uncued distractors. 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 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 type reflects slower responses for conjunction searches (average reaction times of 589 msec for conjunction searches and 551 msec for feature searches).

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 reaction time advantage that is typically found for feature searches (as opposed to conjunction searches). There is no interaction of search type and item numerosity for the 3-cue trials, indicating that the effect of search type is consistent across three items alone and three items cued from among fifteen.

Discussion

The results of Experiment 1 suggest that a number of spatially disparate cued items are processed virtually as if they are the only items in the display. There is an expected overall cost of filtering the cued items from among uncued distractors (see Treisman, Kahneman and Burkell, 1983).

Search over late-appearing (cued) items is slower when those items appear with additional uncued distractors in a fifteen-item displays than when they appear alone in the display. Nonetheless, search over a subset of cued items selected from a larger display is speeded relative to search over the entire set of items. Furthermore, search over a cued feature subset in 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. In particular, the feature search advantage observed in the three-item displays is replicated when three items are cued among fifteen.

It is important to note that the advantage for feature subsets over conjunction subsets implies that at least two (and probably all three) of the subset are simultaneously indexed and selectively processed. A reaction time advantage is predicted for subset search even if only one of the cued items is selected; a reaction time difference between feature subset search and conjunction subset search is only predicted if more than one of the cued items is selectively processed. The distinction between feature subsets and conjunction subsets does not exist for a single item, because a single item cannot form a set of homogeneous or mixed distractors. Suppose, for example, that subjects do not select the entire subset but instead select one of the items in the subset. In this case facilitation (in the form of reduced reaction times) would be observed whenever a subset of objects is cued. The facilitation would arise from the one-third probability that observers correctly choose the single place holder marking the subsequent location of the target (on target-present trials). Selective processing of a single cued item could, therefore, explain a reaction time advantage for cued-subset search. But single item sampling cannot form either a conjunction set or a feature set, and thus single item selection cannot explain a reaction time advantage for feature sets over conjunction sets. Consequently, the single-item sampling hypothesis could not account for the difference in search times between feature search and conjunction search conditions.

Experiment 2: Effect of Number of Cued Items in Subset Search

Experiment 2 provides a further test of the hypothesis that indexed items are treated as if they are the only items in the display, by systematically investigating the effects of increases in the number of cued items. There are three independent variables manipulated in this experiment: number of cues (2, 3, 4, 5); cued subset type (feature set, conjunction set); and target condition (target-present, target-absent). It is predicted that the pattern of reaction times for cued-subset search will resemble the pattern of reaction times predicted by models of traditional visual search. Specifically, based on models of visual search (e.g., FIT, proposed by Treisman and Gelade, 1980; Guided Search, proposed by Wolfe, Cave, and Franzel, 1989, and modified in Wolfe, 1994; and a competitive interaction model proposed by Duncan and Humphreys, 1989), it is predicted that: 1) feature subset reaction times will increase very little with each added distractor, and the reaction time pattern for feature subset target-present and target-absent responses will be very similar; 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.

Apparatus and 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 2 were identical to those used in Experiment 1. The following description explicitly notes those ways in which Experiment 2 differs from Experiment 1.

Pilot research with the cued-subset search task indicated that selection of a subset of items becomes increasingly difficult as the number in the subset increases. Therefore, to aid and encourage subjects to process selectively the late onset items, the experiment design was altered in two ways. First, a small number of highly practised subjects served as the observers for this experiment, under the assumption that experience would lead to an improvement in the ability to maintain indexes on a larger number of cued objects. Second, the displays were designed so that the search task could not be completed accurately unless the identity of the cued items was 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 cued items; the modification of the displays ensured that the entire display was not being searched in lieu of cued-subset search over the indicated subset.

Each display consisted of a total of 24 items: 8 items matching the target in both colour and orientation (the cued subset included either 1 or 0 of these 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. In all other respects, the stimuli were identical to those used in Experiment 1.

Procedure. There were three independent variables manipulated in each experimental session: number of cues (2, 3, 4, 5); cued subset type (feature, conjunction); and target condition (target-present, target-absent). The cued target appeared once in each of the 36 possible display positions within each combination of number of cues and cued subset type. Target-absent trials were constructed by replacing the cued target with a distractor item, selected to maintain cued distractor homogeneity for the feature subset trials. Each session included 36 trials in each possible combination of number of cues, cued subset type and target condition. 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 cued subset 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 cued subset 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 Experiment 1. 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).

Results

The data from four subjects are reported in this experiment. [5] The proportion of errors and average reaction time were calculated for each subject in every combination of number of cues (2, 3, 4, 5), cued subset 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, 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).

Due to the fact that target-like items were included among the uncued items, errors were defined differently in the current experiment than in Experiment 1. Displays in the current experiment include false targets among the uncued items; the task of the subject was to identify whether a target was included among the cued subset. Thus, in the current experiment an error was defined either as a target in set response when there was no target in the subset, or a no target in set response when a target was in fact included over the cued items. As in Experiment 1, trials immediately following an error were discarded from 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 resulted in the elimination of between 4.4% of trials (3 cues, conjunction subset, target-absent) and 19.5% of trials (5 cues, feature subset, target-absent).

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), cued subset type (feature, conjunction), target condition (target-present, target-absent) and level of practice (less, more) as independent variables.

The analysis of variance for error data (across subjects) revealed a number of significant effects. There was an observed decrease in the proportion of errors with increased practice (6.6% errors for less practice, 4.9% errors for more practice, $F_{(1,3)}=17.19$, $p<.05$). Subjects made fewer errors in the feature subset condition as opposed to the conjunction subset condition (4.8% errors for feature subsets, 6.7% errors for conjunction subsets; $F_{(1,3)}=11.01$, $p<.05$), 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 was a significant effect of number of cues ($F_{(3,9)}=15.82$, $p<.05$). There was 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 were also two significant interactions in the error analysis: number of cues by cued subset 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 was greater for conjunction subsets (error rates of 1.8%, 3.9%, 8.1% and 13.3% for 2, 3, 4, and 5 cues) than for feature subsets (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) increased at a slower rate than did 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 revealed the predicted interaction of number of cues, cued subset 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), cued subset type ($F_{(1,3)}$=31.99, p<.05) and target condition ($F_{(1,3)}$=11.94, p<.05) were subsumed under this significant three-way interaction, as were the interactions of number of cues by cued subset type ($F_{(3,9)}$=13.54, p<.01), number of cues by target condition ($F_{(3,9)}$=4.18, p<.05), and cued subset type by target condition ($F_{(1,3)}$=66.95, p<.01).

The three-way interaction, presented in Figure 4, reveals the predicted pattern of reaction times. In particular, the effect of number of cues appears to be greater for conjunction subsets that for feature subsets. Furthermore, within the conjunction subsets there is a greater effect of number of cues for target-absent trials than for target-present trials. To explore this interaction further, the effect of number of cues was examined within each combination of cued subset type and target condition using Tukey's HSD (critical q=5.95). For feature subsets, the difference in reaction time between the two cue condition and the five cue 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=1.41) or target-present trials (means of 523 msec and 574 sec for two cues and five cues respectively, q=2.88). In contrast, for conjunction subsets both differences reached significance (for target-absent trials, means of 562 msec and 731 msec for two cues and five cues respectively, q=9.54; for target-present trials, means of 520 msec and 641 msec for two cues and five cues respectively, q=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 subsets. 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 0.49:1).

Insert Figure 4 about here.

The observed slopes for feature subsets are unusual in two respects: first, for these subsets, both the target-present slopes and the target-absent slopes are unusually high; second, the target-present slopes are almost twice the target-absent slopes. The unusual pattern of slopes holds for three of the four subjects who participated in the experiment, and thus does not seem attributable to the small number of subjects in the experiment (see Table 1). The second aspect of this unusual pattern of reaction time slopes appears to hold only when 2-item subsets are included in the analysis. The slopes for subsets numbering from 3 to 5 are: conjunction subsets, target-absent, 49 msec/item (98.6% of variance accounted for); conjunction subsets, target-present, 24 msec/item (99.3% of variance accounted for: conjunction subset target-absent to conjunction subset target-present ratio 2:1); feature subsets, target-absent, 13.5 msec/item (99.6% of variance accounted for); feature subsets, target-present, 15.5 msec/item (72.6% of variance accounted for: feature subset target-absent to feature subset target-present ratio 0.87:1).

Insert Table 1 about here.

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 ($F_{(1,3)}=6.74$, $0.05<p<.1$). 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 cued-subset search becomes more efficient with practice (overall average reaction times were 610 msec for less practice, 573 msec for more practice).

Discussion

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

There is a tendency for error rates to increase with the number of items in the subset, particularly for conjunction subsets. There is also a tendency toward more false negative, as opposed to false positive errors; this tendency increases with subset size. These effects may reflect the difficulty in maintaining larger number of indexes. It is possible that indexes are more likely to be displaced off cued items as the number of indexes increases. Misplaced indexes would result in more false negative errors than false positive errors (as observed in this experiment), because the majority of uncued items on each trial (approximately 2/3) are distractors rather than false targets.

In most respects, the significant interaction of number of cues, cued subset 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). Furthermore, as predicted, search among feature subsets shows less influence of the number of cued items.

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 increase in reaction time with each additional item for the feature subset trails (9 msec per item overall), particularly for target-present trials (18.5 msec per item). This unusual result holds for three of the four subjects in the experiment. The slope discrepancy between feature subset target-absent trials and feature subset target-present trials is reduced when subsets of size 2 are eliminated from the slope calculations; the slopes, however, remain relatively high. Under these conditions, the slopes are 13.5 msec/item for feature subset target-absent trials, and 15.5 msec/item for feature subset target-present trials.

From these results, it is impossible to determine if the unusual slopes for the feature subset condition arise from the small size of the subset (cf. Pashler, 1987), or whether they reflect a special type of processing required for the cued-subset search process. Before these 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 2a examines search among small numbers of abrupt onset items when the search displays do not also include other uncued distractors.

Experiment 2a: Search Among Small Numbers of Abrupt Onset Items

The literature on visual search provides some evidence (e.g., Pashler, 1987) that search among small numbers of items may rely on processes that are different from those used in displays including larger numbers of items. The slightly unusual pattern of results observed in Experiment 2 could, therefore, be due solely to the fact that observers are searching over a small number of items. Alternatively, this unusual pattern of results could reflect special processing required for subset conjunction search.

In order to distinguish between these two possibilities, Experiment 2a replicates Experiment 2 with the uncued distractors removed from the display. If the cued subset are indeed processed as if they are the only items in the display, the results observed in Experiment 2a should match those observed in Experiment 2. In particular, it is predicted that: 1) feature search reaction times will increase very little with each added distractor, and reaction times for feature search target-present and target-absent responses will be similar; 2) conjunction search 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; 3) finally, the unexpected slope for feature search target-present trials observed in Experiment 2 should be replicated in the current experiment.

Method

Subjects. Four subjects participated in Experiment 2a: each was experienced, through cued-subset search experiments, with the displays and the task used in the current experiment. Each subject was paid $10.00 for their participation.

Apparatus and Stimuli. Displays in Experiment 2a were identical in every respect to displays used in Experiment 2 with the sole exception that uncued distractors were removed from each display.

Procedure. Removal of all uncued items from the displays made the task in this experiment much simpler than the cued-subset search task of Experiment 2, and reaction times were consequently much less variable. As a result, the number of practice trials between blocks was reduced to 5, and the number of sessions was reduced to one. In all other respects, the procedure used in Experiment 2a was identical to that used in Experiment 2.

Results

Average reaction time and proportion errors were calculated for each subject in each combination of item numerosity (2, 3, 4, 5), search type (feature search, conjunction search) 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 items, feature set, target-present trials) to 7.6% (for 5 items, conjunction set, target-present trials).

Repeated measures analyses of variance were conducted separately for the error date and the reaction time data. Independent variables in the analyses were number of cued items (2, 3, 4 or 5), search type (feature search, conjunction search), and target condition (present, absent).

Error rates ranged from 0% (4 items, conjunction search, target-absent) to 7.5% (4 items, conjunction search, target-absent). The error analysis revealed no significant effects, although the effect of number of items was marginally significant ($F_{(3,9)}$=3.48, p=.064; error rates of 2.8%, 2.8%, 3% and 4.9% for 2, 3, 4, and 5-item displays).

The reaction time analysis revealed three significant main effects (item numerosity: $F_{(3,9)}$=38.38, p<.01; search 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. 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=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 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 trials (513 msec) than to conjunction search trials (578 msec). In addition to these significant main effects, there was a significant interaction of item numerosity by search type ($F_{(3,9)}$=13.13, p<.01). Tests of means (using Tukey's HSD; critical q=4.82) indicated that, for conjunction searches, 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 searches, 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 type and target condition was marginally significant ($F_{(3,9)}$=3.26, 0.05<p<.1). Within this marginal interaction, reaction time slopes (over number of items) were calculated for each combination of search type and target condition. Calculated slopes for feature searches 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 searches 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). For the purposes of comparison to the results of Experiment 2, this marginal 3-way interaction is presented in Figure 5.

Insert Figure 5 about here.

Reaction time slopes were calculated for subsets of size 3, 4, and 5. The observed slopes were: feature subsets, target-absent, 9.5 msec/item (41.6% of variance accounted for); feature subsets, target-present, 14.5 msec/item (62.4% of variance accounted for: feature subset target-absent to target-present ratio 0.66:1); conjunction subsets, target-absent, 30.5 msec/item (99.9% of variance accounted for); and conjunction subsets, target-present, 24.4 msec/item (84.2% of variance accounted for: conjunction subset target-absent to target-present ratio: 1.25:1).

Discussion

Most aspects of search performance in Experiments 2 and 2a conform to predictions of theories of visual search. Target-present responses are faster than target-absent responses, and responses are generally faster for feature searches as opposed to conjunction searches. Both experiments reveal a reaction time advantage for feature search displays that increases with the number of items to be searched (either the number of items in the subset, as in Experiment 2, or the number of items in the entire display, as in Experiment 2a). Finally, in conjunction searches the target-absent reaction times increase at a faster rate than target-present reaction times, although the slope ratio does not approach the 2:1 ratio that would indicate typical serial search. These results suggest that neither the relatively small numbers of items nor the unusual presentation procedure substantively alter the process of visual search.

Although it is not predicted by theories of visual search, the unexpectedly large reaction time slope for feature search trials observed in cued-subset search (Experiment 2) is nonetheless replicated in regular feature search in the current experiment. The results of the current experiment do not offer an explanation of this unexpected finding. They do, however, serve to rule out one type of account. In particular, the unexpected result cannot be attributed to factors specific to the subset search process.

Taken together, the results of Experiments 2 and 2a suggest that observers are able to functionally extract five (and possibly more) items from a larger display, and subsequently selectively apply attentional processes used in visual search to those items.

Experiment 3: Effect of Spatial Dispersion of Cued Items

The results of Experiments 1 and 2 suggest that observers can select a subset of display items, and subsequently perform a search for a conjunction target that is restricted to the selected items. This result is consistent with the FINST 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, by hypothesis, an indexed object can be accessed directly without the need for an attentional scan through the intervening space.

Most attentional theories (e.g., spotlight theory; LaBerge, 1983; Posner, 1980; Posner et al., 1980; or zoom lens theory; Eriksen and St. James, 1986; Eriksen and Webb, 1989; Eriksen and Yeh, 1985) predict that search performance should decline (i.e., reaction time should increase) as the distance between the items increases (e.g., Castiello and Umiltà, 1990; Egeth, 1977; Eriksen and St. James, 1986; Henderson, 1991; LaBerge, 1983; LaBerge and Brown, 1989; Posner et al., 1980). This effect is assumed to reflect either the time required to scan between items (under the spotlight theory), or the decrease in processing resources available at a particular location when the resources are spread over a larger area (under the zoom lens theory).

In contrast with unitary-attention theories, FINST theory assumes that individual markers are placed on each of the indexed items, and that these markers facilitate immediate access to the items. 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 spatial dispersion of the set of marked items.

Notwithstanding the evidence of distance-dependent access-time for items in the visual field (e.g., Shulman, Remington, and MacLean, 1979; Tsal, 1983; Egly and Homa, 1991), there is considerable evidence that attention can be switched between salient objects in the visual display in a length of time that is independent of the distance between them (e.g., Sagi and Julesz, 1985a; Eriksen and Webb, 1989; Kwak, Dagenbach, and Egeth, 1991; Remington and Pierce, 1984; Rizzolatti, Riggio, Dascola, and Umiltà, 1987; Sagi and Julesz, 1985b, 1985c). The considerable amount of evidence suggesting time-invariant shifts of attention when there are indexed items in the display supports the hypothesis of direct access to indexed locations, as suggested by the FINST theory.

Experiment 3 offers an explicit test of this hypothesis in the context of subset-search studies, where there is independent reason to believe that the items in the subset have been indexed. Three conditions were manipulated in the experiment: spatial dispersion (the levels of this variable are explained in method section); subset type (feature subset, conjunction subset); and target condition (target-present, target-absent).

Method

Subjects. Eight University of Western Ontario students were paid $10.00 to participate in one 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.

Apparatus and Stimuli. The stimuli used in Experiment 3 were identical to those used in previous experiments, as was the sequence of events on every trial. The differences between Experiment 3 and previous experiments are described in this section.

Each display in Experiment 3 included twelve items, evenly spaced on the circumference of a circle centered at fixation. Subjects were told to fixate the center of the display. In pilot experiments, the combination of fixation maintained at the center of the display and a fixed set of display locations led to some adaptation and afterimages. Therefore, in order to combat this effect, the display positions were perturbed a small amount between trials by alternating between two sets of positions, evenly spaced on circles of different sizes.

From a viewing distance of 100 cm, each object subtended 0.7 degrees. Each of the twelve objects was 2.9 degrees from fixation for the smaller circle, and 3.4 degrees from fixation for the larger circle. The distance between nearest contours of adjacent objects was 0.9 degrees for the smaller circle and 1.1 degrees for the larger circle.

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 equidistant 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 (see Figure 6). 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 degrees for the small radius (2.0 degrees large radius) for dispersion 0, 3.1 degrees for the small radius (3.7 degrees large radius) for a dispersion 1, 4.5 degrees for the small radius (5.4 degrees large radius) for a dispersion 2, and 5.7 degrees for the small radius (6.3 degrees large radius) for a dispersion 3. 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.

Insert Figure 6 about here.

Each search display included either 12 distractors, or 11 distractors plus one target. Distractors were always mixed. In each display, the two types of distractors appeared in approximately equal numbers (for target-absent trials, the number of each type of distractor was 6; for target-present trials, one distractor was replaced by a target). In every trial, three 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.

Procedure. Targets were constrained to appear in every second display position (a complete counterbalancing of all factors over every target position resulted in too many trials to be completed within one session). Within each combination of dispersion and subset 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 subset type (see Figure 6 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 subset type (feature subset, conjunction subset). Target-present and target-absent trials were randomly intermixed in each block, as were trials at the various levels of dispersion. The two types of feature subset trials (distractor matching the target in colour, and distractor matching the target in orientation) were randomly intermixed in the feature subset blocks. Thirty-six practice trials preceded each of the feature subset and conjunction subset blocks. Subjects were given the opportunity for a rest break every 72 trials.

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

Results

Average reaction time and proportion of errors was calculated for every combination of dispersion (0, 1, 2, 3), subset type (feature subset, conjunction subset) and target condition (target-present, target-absent). Errors were defined as in Experiment 1. As in previous experiments, 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 exclusion of between 2.1% of trials (dispersion 1, feature set, target-present) and 8.3% of trials (dispersion 2, conjunction subset, target-present) of the trials in each cell.

Error data and reaction time data were analyzed in separate repeated measures analyses of variance with target condition (present/absent), subset type (feature set/ conjunction set) and dispersion (0, 1, 2 or 3) as factors.

Error rates ranged from 0.8% (dispersions 1 and 2, feature subset, target-absent) to 9.9% (dispersion 0, conjunction subset, target-absent). The effects on error rates of target condition (present, absent), subset 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 subset type ($F_{(1,7)}=7.68$, $p<.05$), and the interaction of target condition by subset type ($F_{(1,7)}=11.91$, $p<.05$). The main effect of subset type reflects the fact that subjects make significantly more errors in the conjunction subset condition (5% errors for conjunction subsets, 2.6% errors for feature subsets). 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 subsets, 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=4.11) revealed that none of the pairwise differences were significant (largest obtained q is 2.96, for the comparison of target-absent feature subset and conjunction subset error rates).

The reaction time analysis revealed a main effect of target condition ($F_{(1,7)}=14.00$, $p<.05$), a main effect of subset type ($F_{(1,7)}=14.27$, $p<.01$), and an interaction of these two factors ($F_{(1,7)}=6.32$, $p<.05$). The main effects can be interpreted as follows. Reaction times were 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 subset was 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=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 subsets (target-present, 583 msec; target-absent, 641 msec), than for feature subsets (target-present, 566 msec; target-absent, 587 msec).

In addition to these predicted effects, the analysis revealed only one other significant effect: a main effect of dispersion ($F_{(1,7)}=4.56$, $p<.05$; see Figure 7). Inspection of the mean reaction times for each level of dispersion, however, revealed 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 for 0, 1, 2 and 3 item dispersions were: 581 msec; 612 msec;

598 msec; 586 msec, respectively). None of the pairwise comparisons was significant by Tukey's HSD (critical q=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.

Insert Figure 7 about here.

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 ($F_{(1,7)}=4.46$, $0.05<p<.1$, 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), subset type (feature set, conjunction set) and dispersion (0, 1, 2, 3). The effect of dispersion was significant in four of the eight individual subject analyses. In three of the four cases of a significant effect of dispersion, the pattern of reaction time over dispersion was identical: fast reaction times 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. For three of the four subjects, the reaction times were significantly faster for a dispersion of 0 than for a dispersion of 1 (by the Tukey-Kramer Modification of the HSD test; Kirk, 1982). For two of the four subjects, the effect of dispersion remained significant when trials with a dispersion of 0 were removed from the analysis (this effect is marginal, $0.05<p<.1$, for a third subject).

Discussion

The results of Experiment 3 replicate the basic finding of Experiments 1 and 2: searches for conjunction targets are faster among feature search subsets than among conjunction search subsets. This experiment extends the previous results by demonstrating that subset search reaction times do not increase with increased dispersion of the cued items, providing strong evidence against models of processing which require scanning between the objects that are to be examined.

Although there is no evidence of a general increase in reaction time with increased dispersion, there is a significant effect of dispersion which takes an unexpected form. There appear to be two aspects to this dispersion effect: 1) fast reaction times 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) might be due to facilitation as a result of 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 could result in speeded processing for all members of the cued subset, simply by virtue of the greater visual acuity in the foveal region. When the objects do not occupy adjacent 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 are most likely to 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.[6]

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 cued 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. It should also be noted that this effect cannot be attributed to sensory interactions between nearby display items (Levi, Klein, and Aitsebaomo, 1985), as the number of items in the display, and thus the distance between each item and its nearest neighbours, does not differ with cue dispersion. Instead, the effect must be attributed to interactions specifically among indexed items, independent of interspersed non-indexed items.

The general reduction in reaction time with an increase in the dispersion between cued objects (reliably observed for some, but not all, subjects) argues against any theory of attention that requires scanning between indexed objects. Similar results have been reported by Beck and Ambler (1973), who found that cues on opposite sides of the display produced performance that was slightly better than cues indicating adjacent locations in a display. The results of the current experiment cannot be attributed to sensory interactions or crowding of items in the display. The distance between adjacent items remained the same across all levels of cue dispersion. This effect must, therefore, be attributed to interactions between cues and/or resulting indexes.

General Discussion

The results of the three experiments reported in this study support 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.

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, and Burkell, 1983), the pattern of RTs observed for three items cued among fifteen is similar to the pattern observed when the three items appear alone. The results of Experiment 2 indicate that up to five objects can be indexed and subsequently selectively processed, and the results of Experiment 3 suggest that indexed objects are accessed directly, without requiring attentional scanning between objects.

The reaction time advantage for search over subsets of display items cannot be attributed to a strategy of allocating attention to only one of the cued items. The strongest evidence for this claim is the consistent search speed 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 paper). The difference between these two conditions is defined over the set of cued items: feature subsets include homogenous distractors, while conjunction subsets include mixed distractors. If only one of the indicated items were indexed on any trial, the difference between the feature subset and the conjunction subset would simply not exist (since a single distractor cannot form a homogeneous or heterogeneous set).

Further evidence supporting the claim that multiple items are in fact indexed on any trial is provided in the results of Experiment 2. In this experiment, unlike Experiments 1 and 3, 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 by checking other items in the display). If there are false targets in the display, however, a verification strategy will not work, because examination of the entire display will always reveal a number of possible targets. In this experiment, if fewer than the entire subset of cued items are indexed, observers would be forced to rely on a guessing strategy to inform responses. There is, however, no plausible guessing strategy that would produce the degree of accuracy observed in this experiment. Consider the 3-cue condition, assuming that two of the cued items are indexed. Based on the conservative assumption that a target included among two indexed items is never missed, the best possible guessing strategy (if two items are indexed from a set of three) yields an accuracy of 83.3% for the target-present trials; the observed accuracy is 96.9%. [7] The predicted accuracy would decrease if it were assumed that only one of the cued items was indexed. The accuracy of responses in Experiment 2, therefore, argues strongly against the hypothesis that only one item is indexed on every trial.

According to Experiment 3, 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 2, the feature search advantage increases with the size of the cued 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 and Gelade, 1980; Guided Search: Wolfe et al., 1989; Guided Search 2.0: Wolfe, 1994; and a competitive interaction model proposed by Duncan and Humphreys, 1989) the advantage for the feature search arises from feature extraction processes assumed to be applied over the entire visual array. The demonstration of a similar feature search subset advantage in Experiments 2 and 3 suggest that it is possible (and in fact may be necessary) for observers to apply feature extraction processes selectively over the set of indexed items, rather than over the display as a whole. This suggestion arises from the fact that feature extraction processes applied over the entire array would provide exactly the same result for feature search and conjunction search subsets (because it is the indexed subset, and not the display as a whole, that differs between these two conditions). Thus, feature extraction processes applied over the entire array could not produce the observed feature subset advantage. Furthermore, it is evident that the application of these processes is not restricted to one contiguous region in space, sized so that the extent includes all cued items. In all the experiments reported in this paper, cued items are interspersed with uncued items throughout the display, and the feature subset advantage is nonetheless observed. In Experiment 3, the effect of dispersion is explicitly tested, and the results indicate that the feature set advantage does not decrease with increased item dispersion and increases in the number of intervening items. Thus, it appears that both the feature extraction and feature conjunction aspects of the search process can be applied selectively to the cued items, regardless of their spatial dispersion and number (within the limit of the number of indexes, which is assumed to be approximately five). This result supports the FINST theory assumption that indexes provide direct access to indexed locations, obviating the need for an analog scan to move attention between indexed locations.

Since the research reported here was carried out, Watson and Humphreys (1997) have published data showing that under certain conditions observers are able to search selectively over subsets of items numbering up to eight. Unlike the present studies, the experiments of Watson and Humphreys involved temporally segregating the items in a conjunction search display into two feature subsets, each including only one type of distractor, so the results are not strictly comparable. The authors propose a "visual marking" hypothesis to account for these findings. This hypothesis is very similar to the FINST hypothesis except that Watson and Humphreys suggest that the visual marking mechanism operates through de-selection of old items, while the FINST hypothesis suggests that indexed items (in the case of the current experiments, new items in the display) are actively selected. These two accounts cannot be distinguished on the basis of the data presented in either this paper or in the data presented by Watson and Humphreys. Another difference between the two hypotheses is that FINSTs are assumed to be limited in number to approximately 5, while the visual marking hypothesis assumes that the mechanism is not resource limited. Further research will be required to determine if subset search can be performed over subsets of unlimited size when the subsets are defined in terms of index-invoking cues such as item onsets, or whether there is a limit of approximately 5 to the number of items that can be selectively processed in a subset search, as proposed by the FINST hypothesis.

It should be noted that some of the theories of visual search discussed above (the Guided Search Model (Wolfe, Cave and Franzel, 1989; version 2.0, Wolfe, 1994; the Feature Inhibition Hypothesis, Treisman and Sato, 1990) could account for the current results given certain modifications. Specifically, to account for these results, each of the models must be modified to allow feature extraction processes to be applied selectively to the abrupt onset items. This modification is required to account for the feature-subset/conjunction-subset difference reliably observed in the studies reported in this paper.

In order to support this selective feature extraction, the models must first include a mechanism which supports enduring identification a subset of items identified only by their time of onset (and perhaps onset locations). One method to achieve this would be an ‘onset’ feature map, which identifies abrupt onset items. Although neither model explicitly precludes this modification, it should be noted that transient qualities of objects, such as time of onset, have not generally been among the qualities designated as primitive `features'. If it is so treated this raises the question of how the feature can be detected without a comparison of memory for two different states of a display.

Feature extraction over selected items of a display is similar to the Segregation Hypothesis discussed by Treisman and Sato (1990), which is rejected in favour of the Feature Inhibition Hypothesis on the basis of evidence presented in that paper. Selective feature extraction is also consistent with the claim by Friedman-Hill and Wolfe (1995) that `feature modules need not operate as passive one-shot filters' (p549). They assume that feature extraction processes operate recursively, and that they can be applied selectively to items identified by an earlier pass of a feature extraction process (e.g., an orientation feature extraction process can be applied over the `red' items selected on the basis of colour extracted over the entire array). It should be noted that neither the results reported in this paper nor those of Friedman-Hill and Wolfe (1995) are consistent with feature extraction over a unitary attentional window of variable size, as proposed by Treisman and Gormican (1988). Instead, the evidence suggests that the feature extraction process is applied selectively over disjoint and spatially disparate items.

The FINST visual indexing theory and Friedman-Hill and Wolfe's proposal that feature extraction is applied recursively can each account for the selective subset search results. However, the indexing accounts for the present results without additional assumptions beyond those originally made in the theory (as formulated, for example, in Pylyshyn, 1989) and it also predicts the difference between feature and conjunction subset search results and the lack of effect due to spatial dispersion observed in the current experiments. Moreover, the FINST indexing theory also accounts for a wide range of other results, including the tracking results reported by Pylyshyn and Storm (1988) and Pylyshyn and

Sears (1996), phenomena associated with subitizing (Trick and Pylyshyn, 1993, 1994), the multiple-loci of the attention-sensitive line-motion illusion and a number of other results sketched in Pylyshyn et. al. (1994).

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Footnotes

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[2] 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).

[3] 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 <u>type</u> 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 heterogeneous 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.

[4] The authors would like to thank David Irwin for pointing out the unusually low slopes in the 0-cue conjunction condition.

[5] 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.

[6] Preliminary evidence suggests that this hypothesis is correct. One of the subjects showing a significant effect of distance in this experiment (RE) participated in an exact replication in which eye movements were monitored. After eliminating those trials on which an eye movement occurred, the data did not show a speeding of responses at dispersion 0. The significant decrease in reaction time with increased dispersion was, however, still evident for this subject when eye movements were eliminated.

[7] 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 could 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 2, which is 1.9%. Another possibility is that observers correctly guess that the un-indexed cued 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 nonindexed items (each of which 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 nonindexed 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 for target-present responses if only two items among three cued are indexed is:0.667+(1/3*.5)=.833, or 83.3%. The observed accuracy for three-item target-present trials is 96.9%, discounting the hypothesis that only two items among three are indexed.

Table 1

Reaction Time Slopes for Individual Subjects for Subset Sizes 2 to 5, Experiment 2

	Subset Type					
	Feature			Conjunction		
	Absent	Present	Ratio (Absent:Present)	Absent	Present	Ratio (Absent:Present)
S1	12.8	26.1	0.49	85.6	63.6	1.34
S2	4.6	18.9	0.24	42.4	24.3	1.74
S3	14.0	25.1	0.56	51.7	39.7	1.30
S4	3.4	2.0	1.70	42.9	42.9	1.63
Mean	8.7	18.0	0.75	55.7	38.5	1.51
SE	*2.7*	*5.6*	*0.32*	*10.2*	*9.0*	*0.11*
Group	9.0	18.5	0.49	56.5	38.9	1.45

Figure 1. Matrix of possible display positions for Experiments 1, 2, and 2a.

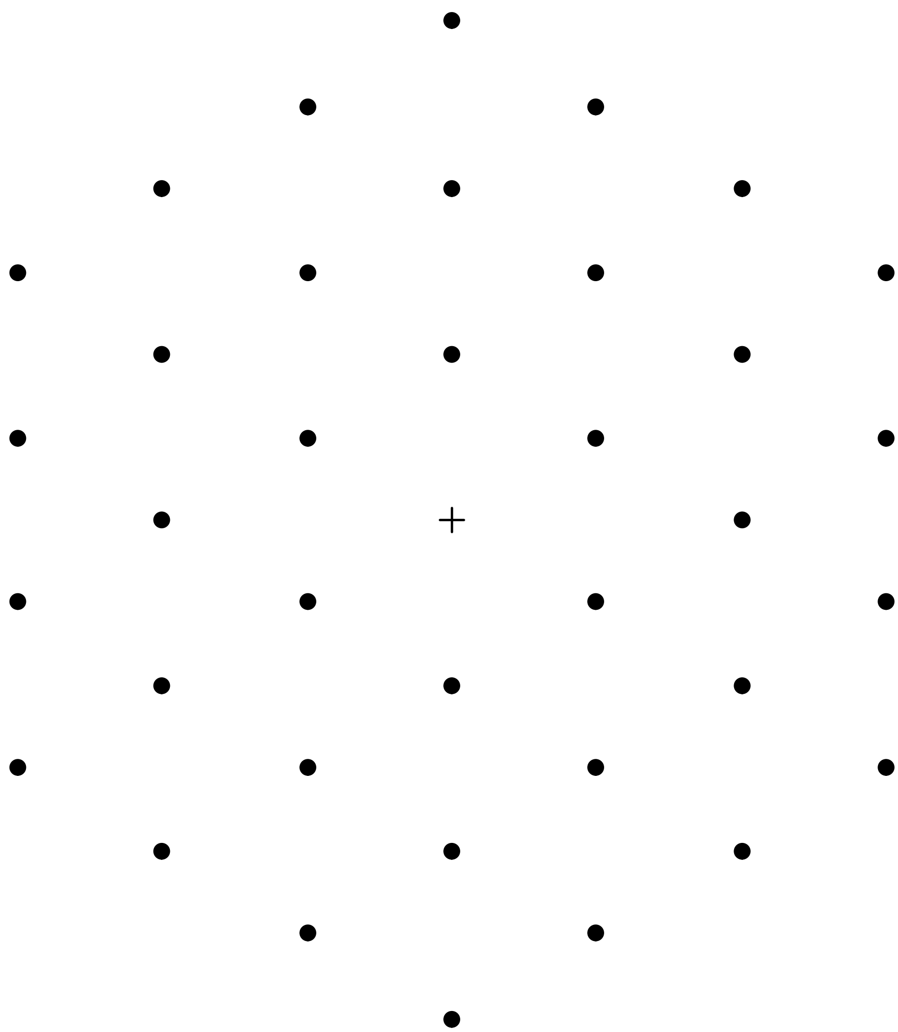
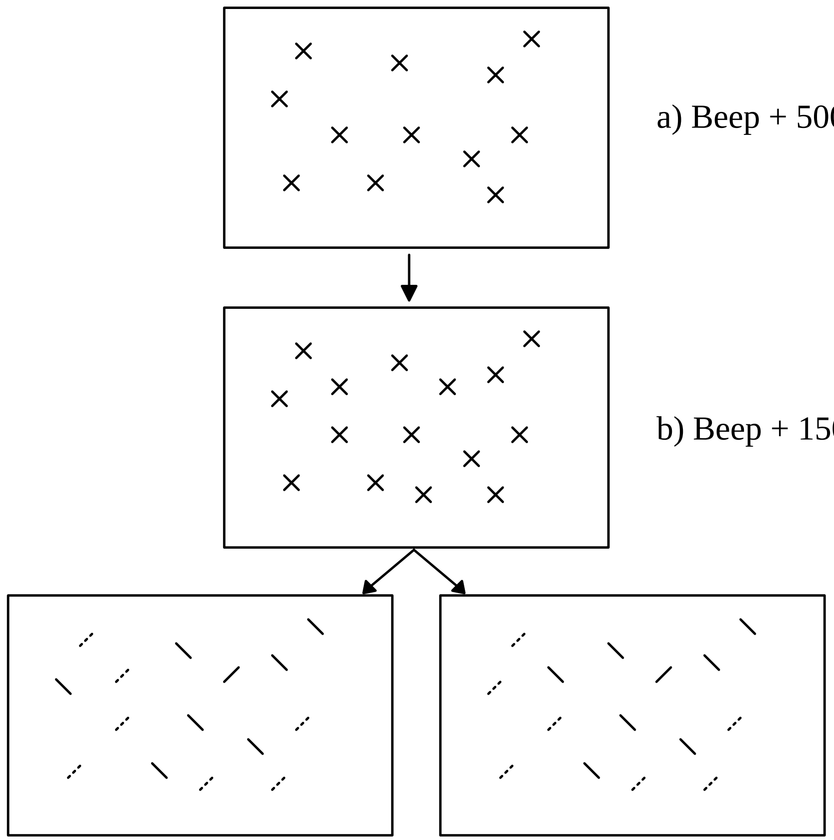


Figure 2. Display sequence for a typical trial. Target item is a right-leaning solid line (note that items in the actual displays differed in colour and orientation, rather than line texture and orientation). Search displays shown in the figure include a target; in target-absent displays, the target is replaced by a distractor, chosen so that distractor homogeneity is maintained for feature subset trials. The sequence of events can be described as follows. At 500 msec after the warning tone (a), the grey X's acting as placeholders for the early-onset items appear. At 1500 msec after the warning tone (b), the placeholder for the late-onset cued items are added to the display. At 1600 msec after the warning tone, and 100 msec after the appearance of the late-onset placeholders (c1 and c2), the search display appears by changing each placeholder to a coloured diagonal line. This change involves the disappearance of one 'arm' of each placeholder, and an isoluminant colour change from grey to red or green. The display that results from this change includes a number of coloured diagonal lines; half of the displays include the target. These displays are constructed so that the subset of items which replace the late-onset placeholders constitute either a feature subset, including homogeneous distractors (c1) or a conjunction subset, including mixed distractors (c2).



a) Beep + 500 msec

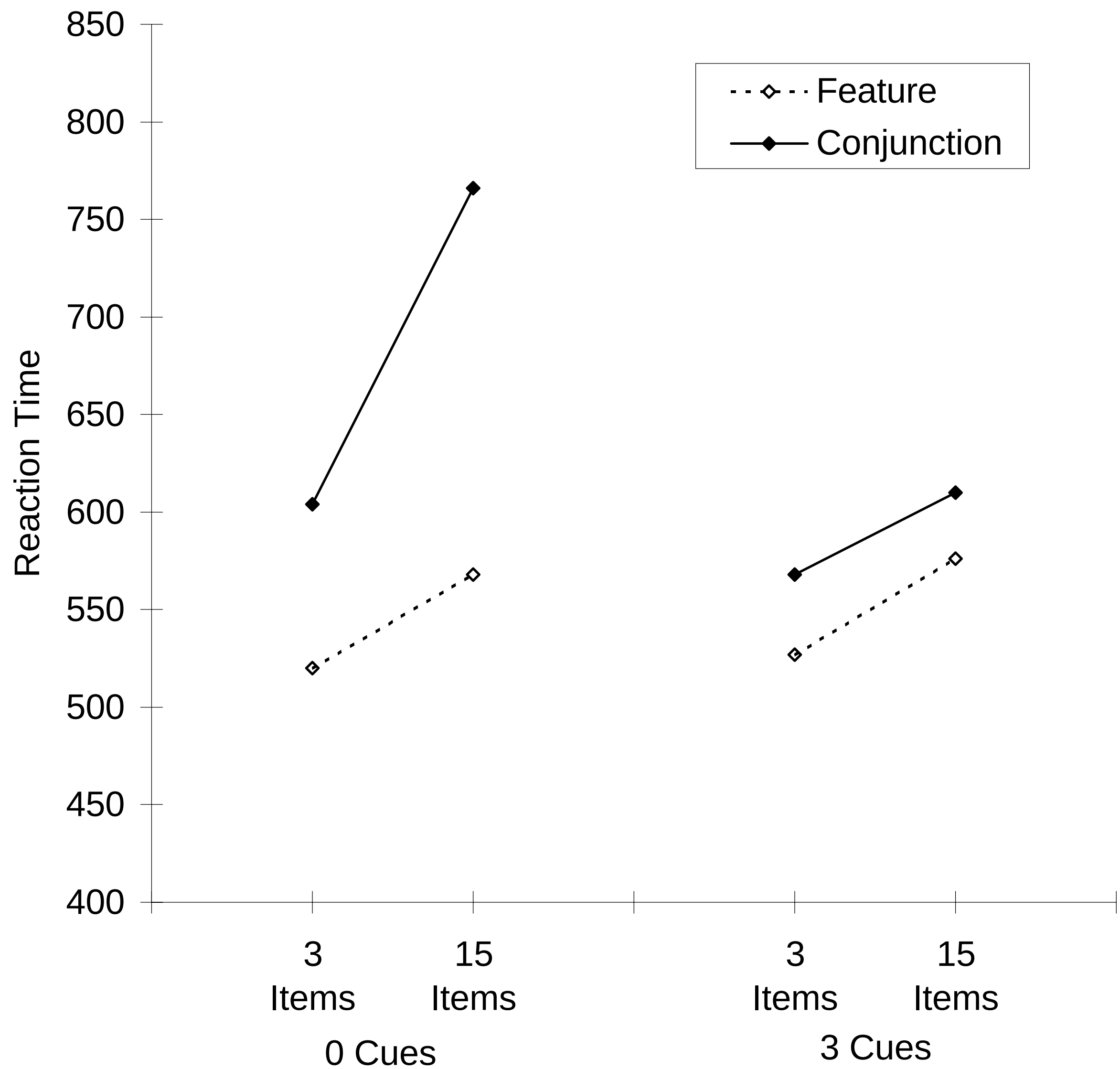
b) Beep + 1500 msec

c) Beep + 1600 msec

c1) Feature Subset

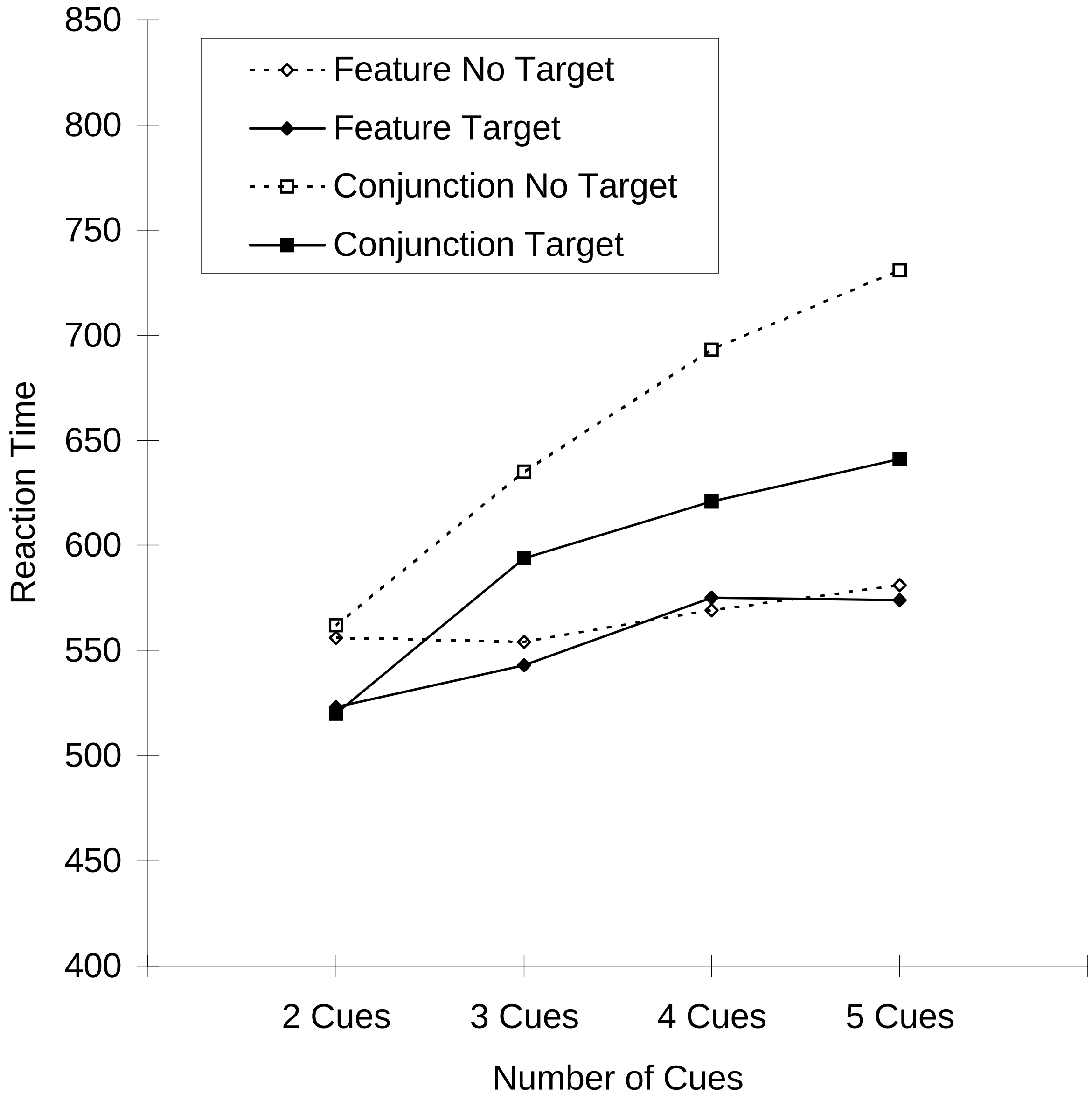
c2) Conjunction Subset

Figure 3. Interaction of number of cues, number of items, and subset type in Experiment 1.



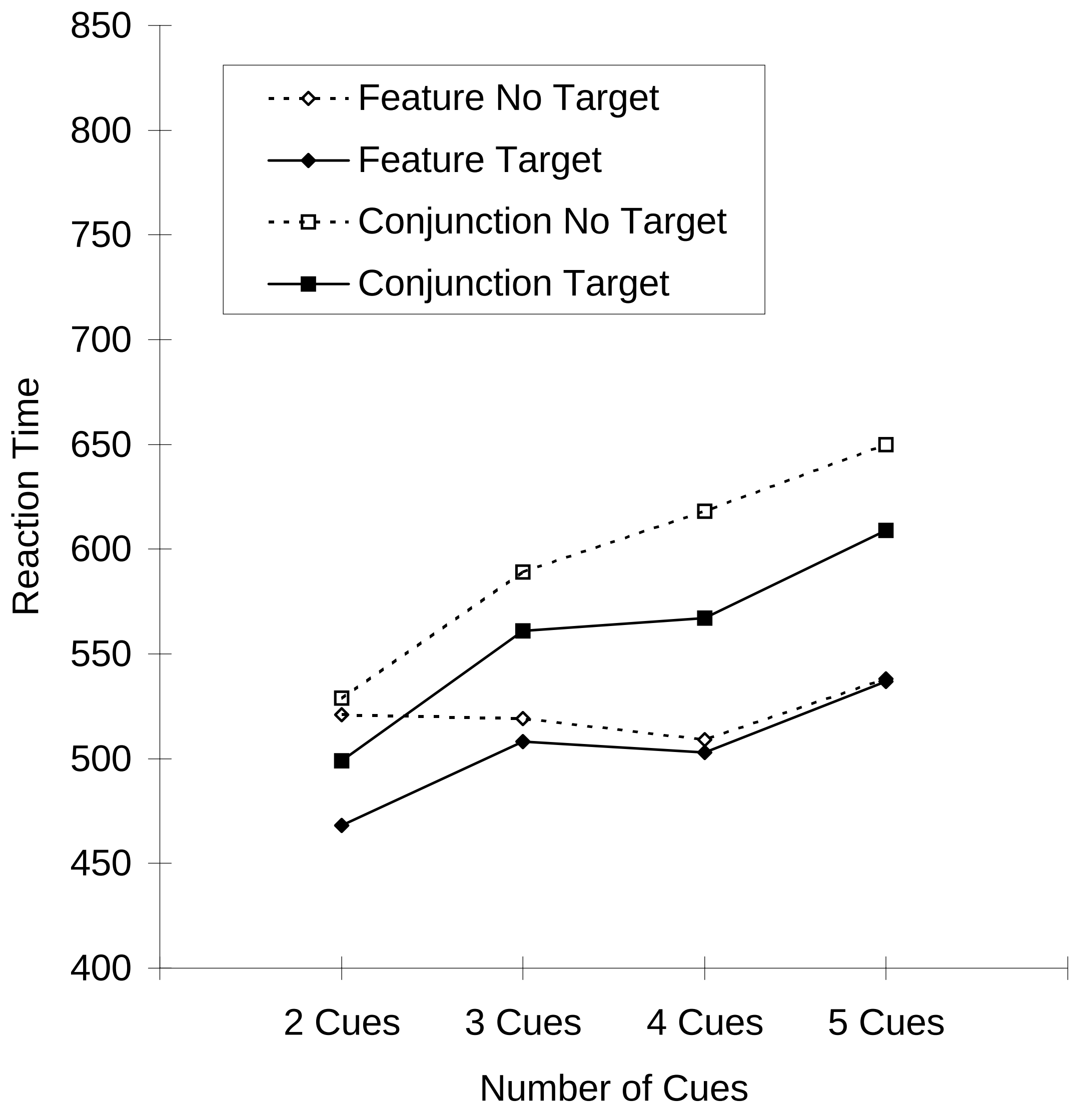
Feature
Conjunction
Reaction Time
850
800
750
700
650
600
550
500
450
400
3 Items
15 Items
0 Cues
3 Items
15 Items
3 Cues

Figure 4. Interaction of number of cues, subset type, and target condition in Experiment 2.



850
800
750
700
650
600
550
500
450
400
Reaction Time
Feature No Target
Feature Target
Conjunction No Target
Conjunction Target
2 Cues
3 Cues
4 Cues
5 Cues
Number of Cues

Figure 5. Marginally significant interaction of number of cues, subset type, and target condition in Experiment 2a.



850
800
750
700
650
600
550
500
450
400
Reaction Time
Feature No Target
Feature Target
Conjunction No Target
Conjunction Target
2 Cues
3 Cues
4 Cues
5 Cues
Number of Cues

Figure 6. Display positions for Experiment 3 (numerical labels are for identification purposes only, and not present in the actual stimulus displays). Sample cued positions for the four levels of dispersion are as follows:

Dispersion 0: positions 12, 1, and 2

Dispersion 1: positions 11, 1, and 3

Dispersion 2: positions 10, 1, and 4

Dispersion 3: positions 9, 1, and 5

Targets appear equally often in the centre of the group (position 1), clockwise of centre (e.g., position 3 at dispersion 1), and counter-clockwise of centre (e.g., position 10 at dispersion 2).

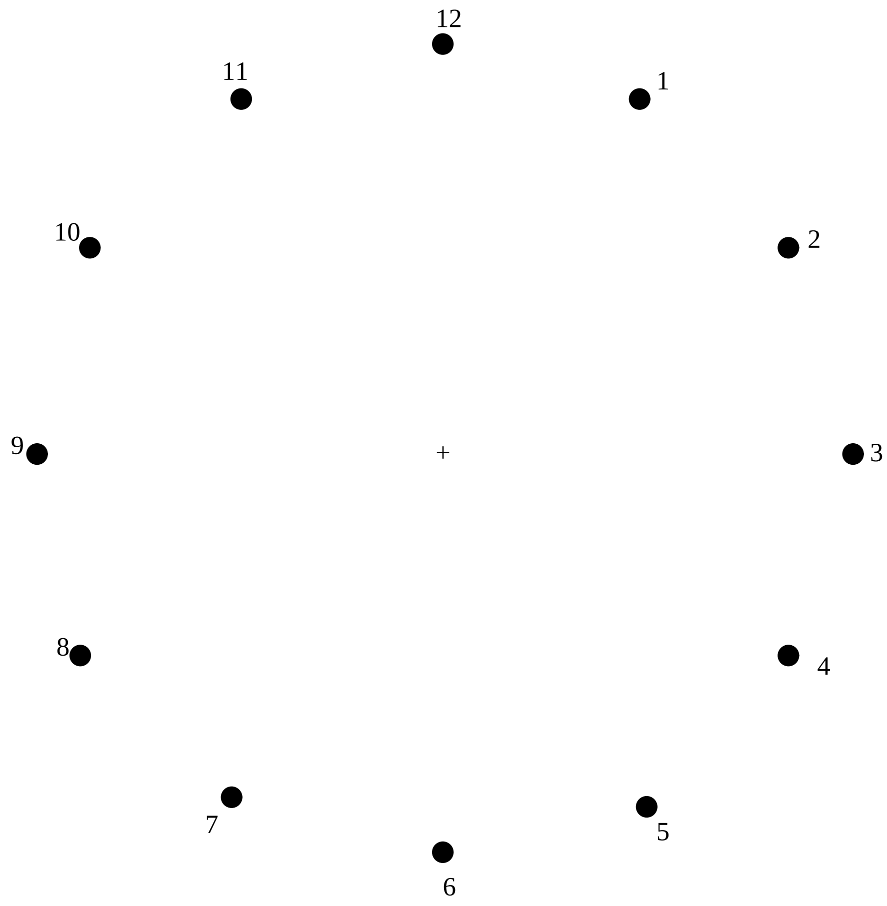
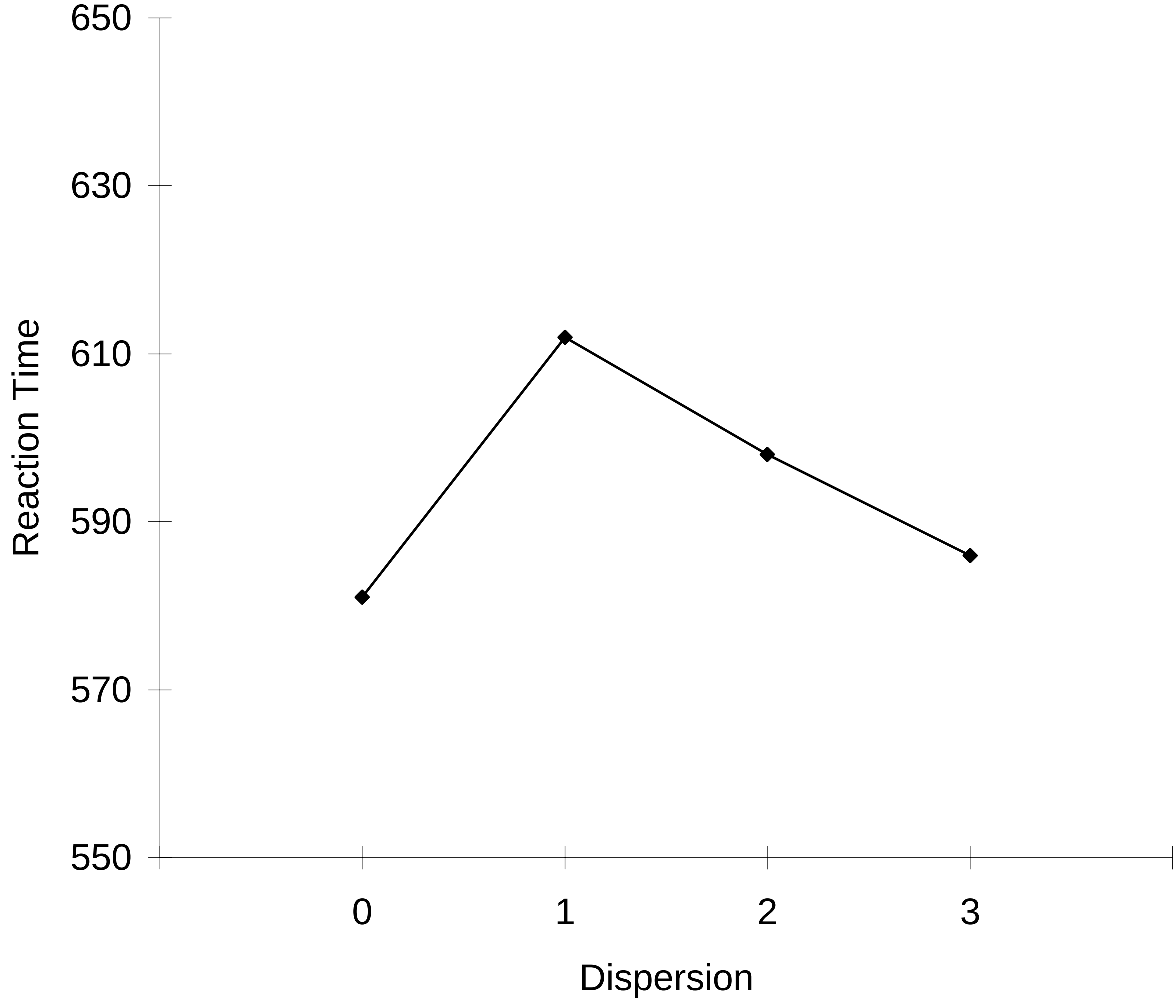

12
1
2
3
4
5
6
7
8
9
10
11
+

Figure 7. Distance effect for Experiment 3.


650
630
610
590
570
550
Reaction Time
0
1
2
3
Dispersion