Research Article

ACCESS TO GLOBAL AND LOCAL PROPERTIES IN VISUAL SEARCH FOR COMPOUND STIMULI

James T. Enns[1] and Alan Kingstone[2]

[1]University of British Columbia and [2]University of California, Davis

Abstract—*The question of whether attention is drawn more easily to global or local aspects of a stimulus has been debated for more than 100 years. We examined it anew, using the visual search task, which distinguishes sensory from attentional effects. Subjects searched for a target feature (e.g., triangle vs. square), which was equally likely to occur in the local elements of a compound search item, in its global structure, or in both. Element size and spacing were used to manipulate whether search was generally easier for local or global targets (e.g., small size and dense spacing favor global detection). The novel result was that these factors had very little influence on search slopes for local targets, whereas they had large effects on search slopes for global targets. This result suggests that a qualitatively different process underlies detection at the global level in traditional compound stimuli. Our proposal that an attention-demanding grouping stage is involved was confirmed in a final experiment in which grouping was made selectively difficult at the local level.*

The visual search task has proven to be a simple but powerful tool in the study of early human vision. In this task, observers try to indicate as rapidly as possible whether a given target item is present in a display. A critical factor is the number of other (nontarget) items that are also present. Because search time tends to increase linearly with this factor, two different measures can be derived: a baseline measure reflecting the sensory, decision, and response components that are engaged on all trials of the task, and a slope measure reflecting the incremental cost associated with selecting the target from a larger set of candidate items (Neisser, 1967; Sternberg, 1969).

All theories of visual search link the baseline measure to an early preattentive stage of processing, in which simple features are registered automatically and in parallel across the visual field (Duncan & Humphreys, 1989; Julesz, 1981; Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989). These same theories link the slope measure to a later attentive stage, in which the spatial relations between visual features are determined by much slower, but also more cognitively active, processes. The theories differ greatly in the specific attentional mechanisms proposed (e.g., serial vs. parallel), but they all share the assumption that slope magnitude reflects the relative involvement of attention in the search task.

Given the wide use of visual search in other areas, we were surprised that it had not been used to study global-local perception. The debate over whether visual analysis begins with the "tree" (i.e., the local element) or the "forest" (i.e., the structured whole) has a long history (Titchener, 1909; Wertheimer, 1925/1955) and has generated many studies (see Kimchi, 1992). The current "textbook" view is that the truth rests somewhere in between (e.g., Coren, Ward, & Enns, 1994; Uttal, 1994). Although there are certainly some conditions that favor global precedence, there are others favoring the local level. Most of the current debate therefore concerns the possible mechanisms implicated when one outcome occurs rather than the other. We therefore use *level precedence effect* to refer in a neutral way to processing advantages for either level.

Interestingly, one class of theories relies on sensory mechanisms to explain the primacy of global perception (Badcock, Whitworth, Badcock, & Lovegrove, 1990; Hughes, Fendrich, & Reuter-Lorenz, 1990). In this view, the global level of a stimulus is linked to a low-pass spatial frequency analysis that is completed more rapidly than an analysis of the higher spatial frequencies. Another class of theories invokes an attentional role instead of (Miller, 1981; Ward, 1982), or in addition to (Shulman & Wilson, 1987), this sensory-based account. But whether attentional effects are a cause or symptom of level precedence has been notoriously difficult to determine (Kimchi, 1992). The visual search task, with its built-in separation between sensory and attentional measures, is therefore a tool that is well matched to this debate.

In this study, we systematically compared search for a distinctive target feature that occurred with equal probability in the local elements of the search items, in their global structure, or in both. Several previous studies have examined search for such features at one level or the other (e.g., O'Connell & Treisman, 1995; Treisman & Gormican, 1988), but none have explored competition or cooperation between levels. It was therefore important to have local and global target features intermixed within a block of trials, to ensure that the search task was not contaminated by the adoption of different strategic sets for the two target levels.

If the sensory account is correct, and level precedence depends on the speed of preattentive feature registration, we would expect factors that influence level precedence to have an additive influence on search times (i.e., only baseline effects). Alternatively, if there is an attentional role in these effects, we could expect multiplicative effects (i.e., slope effects). Such a pattern would indicate that change in perceptual access to a given stimulus level was also accompanied by a change in the attentional requirements.

GENERAL METHOD

Observers searched for a triangle among squares (Experiments 1 and 2) or an oblique bar among vertical bars (Experi-

Address correspondence to J. T. Enns, Department of Psychology, University of British Columbia, Vancouver, B.C., Canada V6T 1Z4; e-mail: jenns@cortex.psych.ubc.ca.

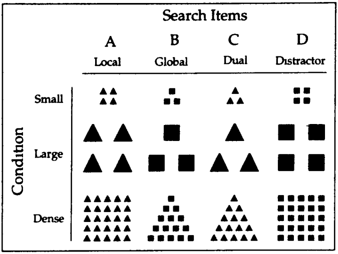

Fig. 1. The compound stimuli in Experiments 1 and 2. Experiment 1 tested the conditions labeled small (compound search items subtended 0.75°) and large (3.00°), Experiment 2 tested small (0.85°), large (2.56°), and dense (2.56°) conditions. Search Items A, B, and C served as equally likely targets among the distractor items (D). Display size was 2, 6, and 10 items in Experiment 1, 2, 4, and 8 items in Experiment 2.

ments 3 and 4). The stimuli were similar in logic to those in previous studies using letter-shape identification and matching tasks (see Kimchi, 1992). For example, in Figure 1, local triangles were arranged to form either global squares (Column A) or global triangles (Column C). Similarly, local squares were arranged in either global triangles (Column B) or global squares (Column D). In the present search tasks, stimuli in Column D served as the distractor items, and those in Columns A through C served as the three equally likely targets (labeled local, global, and dual, respectively) within a block of trials.

A Macintosh computer generated the displays and collected the data. Items were distributed randomly on an imaginary 6 × 4 grid subtending 21° × 14°, as shown in Figure 2. Each item was randomly jittered in its grid location by an amount between −0.25° and +0.25° to prevent influences of item collinearity.

Each trial began with a fixation symbol lit for 500 ms, followed by the search display, which remained visible until the observer responded. A response was followed by a feedback symbol (plus or minus), which served as the fixation point for the next trial.

Right-handed observers with normal or corrected-to-normal vision completed four sets of 60 test trials in each condition (n = 20, 10, 20, and 10 in Experiments 1–4, respectively). The order of conditions within an experiment was counterbalanced. Target presence was reported by pressing one of two response keys. Observers were instructed to maintain fixation at the center of the screen and to keep errors below 10%.

Task instructions emphasized speed, so the main data analyses were of correct response time (RT). There were also systematic differences in accuracy, but in no condition was the reported RT effect contradicted by the accuracy data.

Two RT measures were examined in each experiment, following an initial analysis of variance: the baseline measure observed in the two-item display, and the least squares slope measure over display size. Because all main effects and interactions were significant ($p < .05$), Fisher's (protected t) tests were used to test specifically for differences in these measures.

EXPERIMENT 1

We began with the factor of stimulus size because it can determine whether global or local precedence occurs (Kinchla & Wolfe, 1979; Lamb & Robertson, 1990). The *small* and *large* conditions in Figure 1 were tested in separate blocks, with compound search items subtending 0.75° (small) and 3.00° (large).

The baseline measure, shown as RTs for two-item displays in Figure 3, indicated that the expected global advantage occurred for small displays (local − global = 55 ms, $p < .01$), and the expected local advantage occurred for large displays (global − local = 47 ms, $p < .01$).

The pattern for RT slopes was somewhat more complicated. First, the mean search slope for the local targets (4.8 ms/item) was lower overall than for the global targets (9.6 ms/item, $p < .05$), suggesting that search for local targets was less attention demanding than search for global targets. Second, size had no significant influence on search slopes for local targets (small: 5.5 ms/item, large: 4.2 ms/item, $p > .10$), but it had a significant influence on slopes for global targets (small: 7.8 ms/item, large: 11.3 ms/item, $p < .05$). Third, the baseline global advantage for small displays was accompanied by a marginal global disadvantage in the slope measure (local: 5.5 ms/item, global: 7.8 ms/item, $.05 < p < .10$), whereas the baseline local advantage for large displays was accompanied by a similar local advantage in slope (local: 4.2 ms/item, global: 11.3 ms/item, $p < .05$).

Dual targets tended to be found faster than either the local or the global targets ($p < .01$), and search for large targets was faster overall than for small targets ($p < .01$), but search slopes did not differ with size ($p > .10$).

These data point to an important difference in visual search for local and global targets. Attention is more involved in the detection of global targets. Note that this conclusion arises from the comparison of search slopes, and not from a comparison of total RT, a typical approach in global-local studies. Furthermore, it is supported in two ways: first, by steeper RT slopes for global than local targets, even when baseline RT was faster for global targets (i.e., in the small condition), and second, by the absence of a size-related difference in search slope for local targets (implicating only sensory effects) and the presence of such differences for global targets (implicating attention).

EXPERIMENT 2

Two other factors that influence level precedence are element density (Kimchi, 1992; Martin, 1979; Navon, 1983) and the visual hemifield of presentation (Kitterle, Christman, & Conesa, 1993; Lamb, Robertson, & Knight, 1990; Robertson & Lamb, 1991), with increased density and the left visual hemifield (right hemisphere) both favoring global precedence

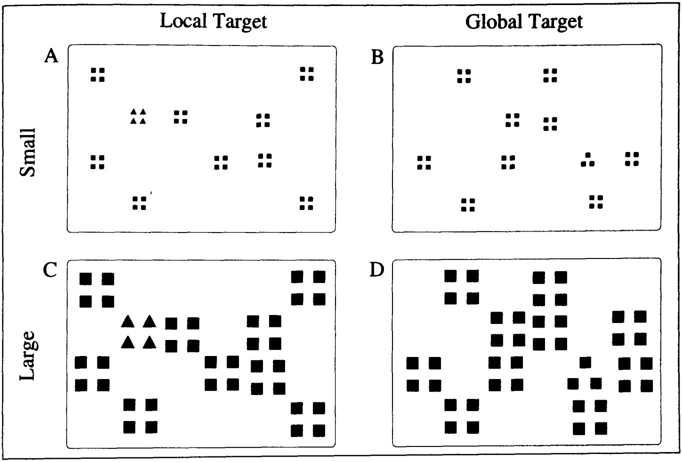

Fig 2 Examples of 10-item search displays (a) local target, small condition, (b) global target, small condition, (c) local target, large condition, and (d) global target, large condition

We modified the search task to permit an assessment of hemifield, following Luck, Hillyard, Mangun, and Gazzaniga (1989) Observers responded to the target location by pressing a key on the same side (e g , for a left-hemifield target, pressing a left-hand key), making no response on target-absent trials On half the trials, all items were presented exclusively in the left or right hemifield, on the other half, all items were evenly distributed across the two fields (Responses were generally faster on bilateral displays, but this did not interact with the other results presented)

In addition to the small and large conditions, a *dense* condition was tested, with elements identical in size and spacing to elements in the small condition, but the overall size of the search items equal to their overall size in the large condition (see Fig 1) These three conditions were tested in separate blocks of trials

The results for the baseline measure, shown in Figure 4, indicated that RTs for local and global targets were approximately equal in the small condition (global − local on two-item displays = 1 ms, $p >$ 10), whereas there was still a local advantage for the large condition (local − global on two-item displays = 46 ms, $p <$ 01) As expected, the dense condition produced a large global advantage (global − local on two-item displays = 84 ms, $p <$ 01) Hemifield analyses revealed a general advantage on the right ($p <$ 01), this advantage was even stronger for local targets than global ones (left − right hemifield = 30 ms for local, 19 ms for global, $p <$ 05), consistent with previous research

The RT slopes, however, again showed a different pattern First, search slopes were generally larger for global than for local targets (small 20 4 vs 4 0 ms/item, $p <$ 01, large 36 4 vs 7 4 ms/item, $p <$ 01, dense 6 2 vs 3 6 ms/item, $p <$ 05), despite the fact that baseline RT varied widely across these conditions Second, size and density did not significantly slow search for local targets ($p >$ 10), but had large effects on slopes for global targets ($p <$ 01) Finally, the slopes for global targets varied predictably with hemifield, with the left hemifield tending to smaller search slopes than the right (20 0 vs 23 0 ms/item, $p >$ 10), although only in the small condition was the difference significant (16 3 vs 26 4 ms/item, $p <$ 01)

Dual targets were found more quickly in the dense condition (2 9 ms/item) than in both the large condition (5 8 ms/item, $p <$ 05) and the small condition (6 7 ms/item, $p <$ 05)

These results confirm that search for global targets is more attention demanding than search for local targets over a wide range of baseline task difficulty This difference is most striking in the dense condition Although there was large global precedence in the baseline measure, search slopes were not smaller for global targets than for local targets in this condition Instead, they were slightly, but significantly, larger This finding suggests that although some stimulus factors affect the preattentive registration of the display (e g , slowing the local information, speeding the global information, or both), they do not necessarily affect search slopes for local targets It was only for global targets that a strong attentional component was implicated

EXPERIMENT 3

In Experiments 1 and 2, search items were very distinctive, triangles and squares differed in edge orientation, number of sides, and overall pixel energy One consequence was that search slopes for local targets were quite small (<10 ms/item) In this experiment, we tested whether the additive effects for local targets generalized to a wider range of search difficulty

The stimuli are shown in Figure 5 Although the specific search items differed somewhat from those used in the previous experiments, the distinctive feature was still oblique orientation, and element density was used to manipulate level precedence The new factor was degree of target distinctiveness, which was varied at both the local and the global levels between easy (45° orientation) and hard (10° orientation) All combinations of task difficulty were run local target (easy, hard) × global target (easy, hard) × density (sparse, dense) Because of the time involved for testing, density was a between-groups variable With the exception of the three target types (local, global, and dual), all conditions were run in separate blocks

The results for the baseline measure (two-item displays), shown in Figure 6, revealed an equal number of conditions of global precedence (A, dense 42 ms, C, sparse 113 ms, C, dense 69 ms, and D, dense 50 ms, all *ps* < 05) and local precedence (A, sparse 50 ms, B, sparse 211 ms, B, dense 132 ms, and D, sparse 147 ms, all *ps* < 05) Thus, our goal of establishing a wide range of level precedence effects was accomplished

Despite the much wider range of task difficulty in this experiment, the slope measure persisted in showing the same pattern Increased density either had no significant influence on search slopes for local targets (A mean slope difference = −7 0 ms/item, $p >$ 05, B mean slope difference = 1 0 ms/item, $p >$ 05) or had an influence that was very much smaller (C mean slope difference = 6 7 ms/item, $p <$ 10, D mean slope difference = 5 9 ms/item, $p <$ 10) than its influence on global targets (A mean slope difference = 14 0 ms/item, B

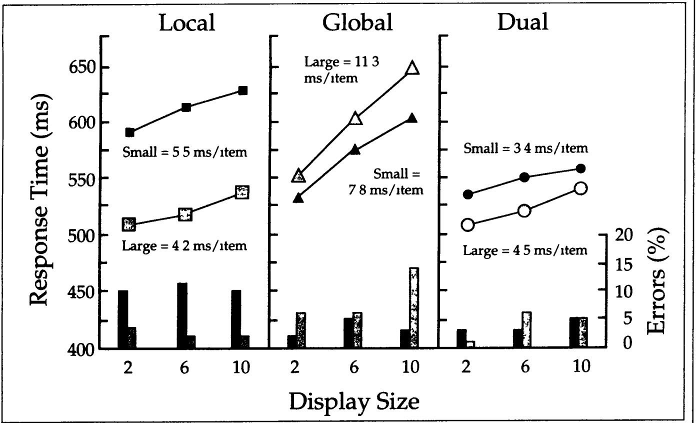

Fig 3 The mean correct response time (RT) and mean percentage errors in Experiment 1 Mean RT slope estimates are given for each display size function, with closed symbols for the small displays and open symbols for the large displays Display size was varied between 2, 6, and 10 items

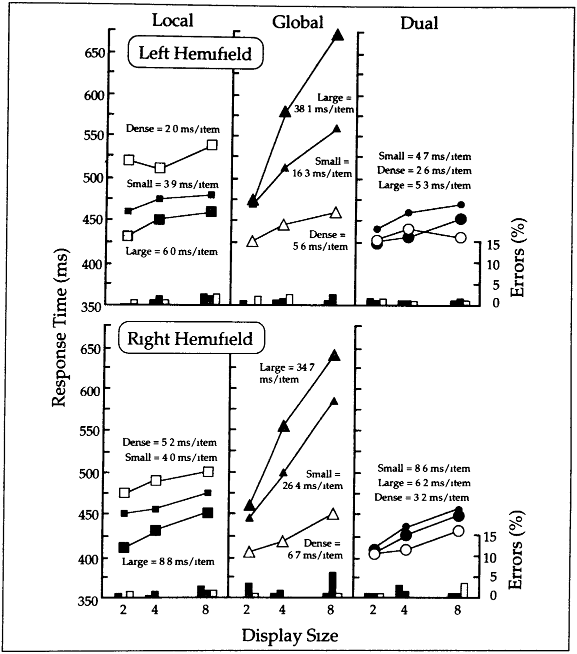

Fig 4 The mean correct response time (RT) and mean percentage errors in Experiment 2 Mean RT slope estimates are given for each display size function, with closed symbols for the small displays, gray symbols for the large displays, and open symbols for the dense displays Display size was varied between 2, 4, and 8 items

mean slope difference = 52 5 ms/item, C mean slope difference = 36 4 ms/item, and D mean slope difference = 46 1 ms/item, all $ps < 01$)

Dense targets tended to be found faster than sparse targets, in both the baseline measure (mean difference = 89 ms, $p <$ 01) and the slope measure (mean difference = 7 2 ms/item, $p <$ 05)

The lack of a density influence on search slopes for local targets in Experiment 2 was therefore not a function of the baseline difficulty of the search task In Experiment 3, even when local targets were relatively hard to detect, producing search slopes clearly in the attentive range (i e , Figs 6c and 6d), element density had an almost negligible influence on local search, in comparison to its very large effects on global search

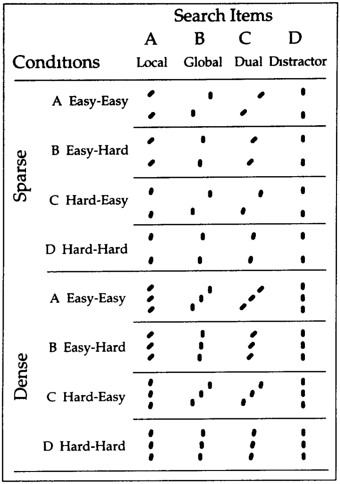

Fig 5 The compound stimuli in Experiment 3 Compound search items subtended 1 2° in their extent, with each local element subtending 0 25° Conditions varied in element density, local target distinctiveness (45°, 10°), and global target distinctiveness (45°, 10°) Display size was varied between 2, 6, and 10 items In the labels of conditions, the first word refers to the local target and the second word to the global target

THEORETICAL IMPLICATIONS

These experiments point to a qualitative difference between detection of a local target and detection of a global target in a compound stimulus This conclusion is not based, as previous claims have been, on differences in total RT between conditions, but is based on the pattern of RT as a function of display size

As described earlier, the visual search task yields two separate RT measures the speed of sensory processes (baseline) and the speed of attentional processes (slope) Although we had no trouble replicating previously reported level precedence effects in the baseline measure, two novel findings emerged in the slope measure Slopes were often steeper for global than local targets, even when the baseline measure strongly favored the global target (e g , Experiment 1, small condition, Experiment 2, dense condition, Experiment 3, C, sparse condition), and element size and density influenced the baseline measure only for local targets, but they had very large effects on the slope for global targets Both of these findings implicate attention as playing a larger role in detection of global targets

But why should global targets be more attention demanding? A deceptively simple answer is that detection of global targets requires an additional process of grouping (at least for these compound stimuli) Such grouping is needed both to link the intraitem elements to one another and to segregate the interitem elements away from each other For the moment, we remain neutral on such questions as whether the proposed grouping is low- or high-level, or initiated by data-driven or top-down strategies A more important first step is to establish the need for such a mechanism, on both theoretical and empirical grounds

The theoretical case has been made recently by Palmer and Rock (1994), in their reexamination of the classic problem of perceptual organization Traditionally, Gestaltists have simply asserted the perceptual reality of display elements (e g , Wertheimer, 1925/1955) However, according to Palmer and Rock (1994), " even the perception of a homogeneous dot against a uniform background requires explanation in terms of some process of organization" (p 32) They favor a proposal in which organization begins with regions of "uniform connectedness" (i e , similar lightness, color, and texture) Such regions form the entry level for subsequent operations of grouping (to form superordinate units) and parsing (to form subordinate units) From this perspective, local elements of compound stimuli correspond to regions of uniform connectedness, which can be accessed directly, whereas global targets require an additional operation of grouping

An empirical case for grouping in the detection of global targets can also be gleaned from visual search experiments For instance, clustering the items in a visual search task (i e , grouping by proximity) allows parallel search for distinctive features within a cluster but only serial search between clusters (Treisman, 1982) Other studies have shown influences on search from the similarity among search items (Duncan & Humphreys, 1989), collinearity of interitem lines (Donnelly, Humphreys, & Riddoch, 1991), and three-dimensional relations among intraitem elements (Enns & Rensink, 1990, 1991)

EXPERIMENT 4

If the ease of grouping local elements is really behind the observed differences in local versus global search, then it should be possible to design a set of compound stimuli in which the grouping operation at the local level is impaired, while the degree of grouping required at the global level is left relatively constant Such stimuli would ensure that any attentional effects (slope) would directly reflect the efficiency of grouping operations, and would also show more generally that the importance of grouping is not limited to global level structure

The stimuli used to test this idea are shown in Figure 7 The black dots corresponded essentially to the A, sparse condition of Experiment 3, with the exception that the small, oriented line segments were replaced by pairs of dots The bicontrast dots, however, consisted of an equal mix of white and black dots, with dots of opposite contrast defining the local level of structure With the bicontrast dots, grouping should be difficult at

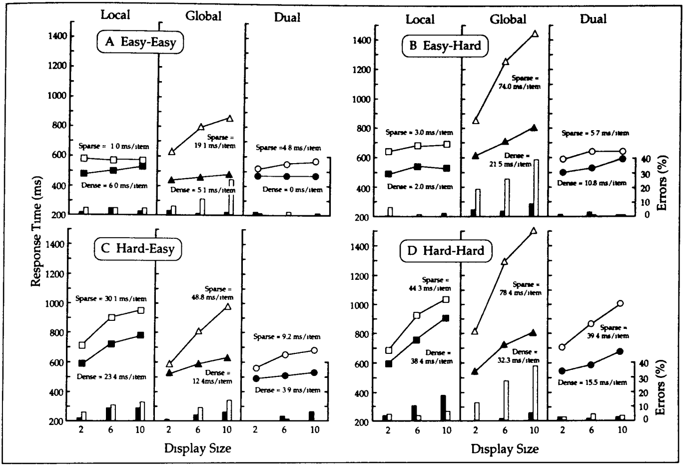

Fig 6 The mean correct response time (RT) and mean percentage errors in Experiment 3 Mean RT slope estimates are given for each display size function Display size was varied between 2, 6, and 10 items The condition labels (A–D) are explained in Figure 5

the local level because of the need to link dots of opposite contrast, but should still be quite easy at the global level, where dots of the same contrast define the shape

As can be seen in Figure 8, the data for the black dots replicated the A, sparse condition of Experiment 3 quite closely Local and global targets were quite similar in the baseline measure (small local advantage of 16 ms, $p >$ 10), with global targets yielding a steeper search slope than local targets (19 4 vs 9 2 ms/item, $p <$ 05) In comparison, the bicontrast dots showed a pattern opposite to that seen in previous experiments Mixing dot contrast at the local level had very large effects on both the baseline (213 ms, $p <$ 01) and the slope (40 4 ms/item, $p <$ 01), but for the global targets, mixing dot contrast had an effect only on the baseline (89 ms, $p <$ 01, slope = 24 9 ms/item, $p >$ 05)

This pattern of data indicates very strongly that the grouping of noncontiguous elements in compound stimuli is an attention-demanding operation, regardless of whether that operation is required at the local or the global level It also emphasizes that attention-demanding grouping operations are not exclusive to the perception of global structure It is important in this context to note that almost all compound stimuli used previously to test level precedence effects have been designed so that grouping at the global level is at least as difficult, if not more so, than grouping at the local level (see Kimchi, 1992)

CONCLUSION

These data demonstrate that perception of the global structure in a traditional compound stimulus requires a grouping operation over and above that needed for the perception of the local elements What are some reasonable candidates for such a grouping mechanism? Gestalt theory is of little help because it simply asserts the existence of elements and laws for their organization, without proposing how organization at either level is accomplished (Palmer & Rock, 1994) What is needed is a theory that makes specific predictions concerning the ease with which spatially segregated elements can be grouped Several recent lines of research point in this direction

Some kinds of grouping can result directly from the interactions among the receptive fields of cortical neurons For example, the blurring of the image induced by spatial filtering can account for some aspects of texture perception (Bergen & Adelson, 1988) and global precedence (Badcock et al , 1990, Hughes

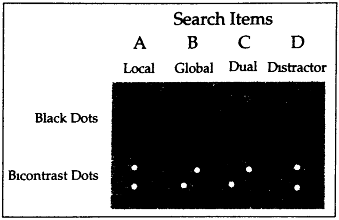

Fig 7 The compound stimuli in Experiment 4 Compound search items subtended 1 25° in their extent, with each dot subtending 0 20°

et al , 1990) Cells in area V2 are even sensitive to subjective contours that arise when spatially separated physical contours are aligned (von der Heydt & Peterhans, 1989), and visual search for targets defined by offset gratings has resulted in pop-out (Gurnsey, Humphrey, & Kapitan, 1992) However, these accounts do not explain why the grouping of global targets is more attention demanding than that of local targets If anything, they predict that global targets should require less attentional effort than local targets

Another kind of theory has emerged from studies of surface interpolation behind occluding objects (Enns & Rensink, in press, He & Nakayama, 1992, Rensink & Enns, 1995) Visual search studies using occluded shapes and textures have indicated that early visual processes parse a display into regions corresponding to discrete surfaces in the scene If the target item corresponds to a salient difference in these surface shapes, the task is relatively easy However, if the target does not correspond to them (i e , it is either an assembly of two or more surfaces or only the visible portion of a larger occluded surface), the task is much more difficult

One prediction based on this account is that search for global targets, much more than search for local targets, should be improved by an increase in element density, a decrease in element size, and a decrease in interelement distance, because these factors all contribute to the interpretation of a textured surface In contrast, variations in target shape (e g , orientation difference) should influence local and global search in a similar way, because whatever grouping operations are needed at each level to determine item shape, they will be completed prior to the shape discrimination operation Both of these predictions were supported in the present data

Regardless of the details that future research may contribute, these visual search data point to important differences in the ease with which attention can be drawn to local and global

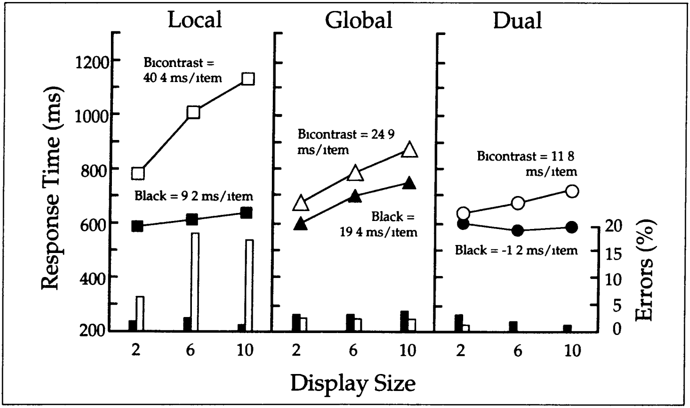

Fig 8. The mean correct response time (RT) and mean percentage errors in Experiment 4 Mean RT slope estimates are given for each display size function Display size was varied between 2, 6, and 10 items

levels of a compound stimulus This finding alone should caution researchers who have previously used comparisons of total RT to make claims about the role of attention in level precedence effects

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