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Measuring Preattentive Processes: When is Pop-out Not Enough?

Lana M. Trick and James T. Enns
University of British Columbia, Canada

Three behavioural tasks (standard visual search, multiple target search, and number discrimination) were tested with a variety of stimuli relevant to two-stage theories of vision. One purpose was to compare the two versions of the search task; a second was to explore the relations between processes of search and enumeration. The two search tasks were quite consistent overall, with strong correlations between search RT slope and multiple target RT gain across stimuli. Analysis of RT slopes for the 1–3 range in the number discrimination task revealed four categories of stimuli: Small slopes (5–40ms/item); moderately large slopes (100–200ms/item); very large slopes (400ms/item or more), and negative slopes (–214ms/item). Although the correlations between number discrimination and the two search tasks were positive, there were several interesting discrepancies, including stimuli with large search slopes and small number discrimination slopes, and those with small search slopes and large number discrimination slopes. These patterns suggest that, at least for some stimuli, subjects may be able to enumerate targets while they are also searching for them, and that search processes sometimes interfere with the processes required for enumeration.

This study had a methodological and an exploratory goal. The methodological goal was to try to resolve the discrepancies between different behavioural methods that have been used to test theories of vision. The exploratory goal was to find out what relation these measures had, if any, with the task of visual enumeration. In this introduction we will begin with a brief discussion of

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Requests for reprints should be addressed to L. Trick, Dept. of Psychology, 2136 West Mall, University of British Columbia, Vancouver, BC, Canada V6T 1Z4. Email trick@unixg.ubc.ca or lanat@kwantlen.bc.ca

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theories of vision and the methods used to test them. Following that, we will discuss visual enumeration.

Theories of vision typically divide visual analysis into two stages (Julesz, 1984; Treisman, 1986; Treisman & Gelade, 1980; Zucker, 1987). The first, *preattentive* stage, registers simple properties at every location in the visual field at the same time. This stage is very rapid, at the cost of being limited to simple visual properties called features. Classic examples include brightness, colour, orientation, length, and curvature. The second, *attentive* stage, can only process a smaller region of the image at a time, but with a larger concentration of resources. This serial stage can perform such sophisticated visual analyses as computing the spatial relations between parts and conjoining different features into one object, but only at the expense of being relatively slow and spatially limited. Although there is no consensus on the specific mechanisms involved in these stages (e.g. Duncan & Humphreys, 1989; Julesz, 1984; Sutter, Beck, & Graham, 1989; Treisman, 1986; Ward & McClelland, 1989) and the original theory has been modified several times to take into account recent findings (Cohen, 1993; Duncan & Humphreys, 1989; Enns & Rensink, 1990, 1991; Epstein & Babler, 1990; Holliday & Braddick, 1991; Humphreys, Quinlan, & Riddoch, 1989; McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986; Ramachandran, 1988; Treisman, 1988; Wolfe, Cave, & Franzel, 1989), the two-stage theory nevertheless provides an elegant account for a large body of findings.

Two behavioural methods that have been used extensively to test theories of vision are the visual search task and the texture segmentation task. In a typical visual search, subjects look for a predefined target item in a field of non-target items. The display remains visible until the subject makes a "present" or "absent" response. The most common measure of performance is the slope of response time (RT) as a function of the total number of items in the display (display size), where slope is analysed separately for target present and target absent trials. If the distinctive target is registered by a spatially parallel mechanism of unlimited capacity, there should be no slope. The target should simply "pop out", regardless of the number of items. When slopes are large, in excess of 10ms/item, it is assumed that search is performed by moving an attentional spotlight serially over the display. Alternatively, the limited capacity of a spatially parallel mechanism may have been exceeded (Townsend & Ashby, 1983).

In typical texture segmentation subjects are shown a densely packed array of microelements and asked to indicate the location or shape of an "odd" region. Displays are brief, often subsequently masked by another pattern, and subjects are given ample time to make as accurate a guess as possible. Accuracy (either percentage correct or *d*-prime) is plotted as a function of the display duration. If the accuracy function reaches asymptote very quickly (i.e. within 50–100ms) the display is thought to contain preattentive features.

It is important to use convergent measures in the evaluation of any theory (Lachman, Lachman, & Butterfield, 1979), and visual search and texture segmentation are assumed to be such convergent measures. The problem is that these tasks don't always converge. Stimuli that pop out in search do not necessarily produce rapid texture segmentation, and vice versa (e.g. Callaghan, 1989; Treisman & Souther, 1985; Wolfe, 1992, 1994). Such discrepancies may indicate that there are several preattentive mechanisms, with different ones being used in each task. Alternatively, discrepant findings may simply be an artifact of task differences that are unrelated to attention. Among other things, the tasks differ in (1) the spatial density and temporal duration of the displays (sparse and long for visual search vs. dense and brief for texture segmentation); (2) the use of pattern masking in texture segmentation; (3) the features potentially useful to subjects (e.g. single item in visual search vs. a region of items in texture segmentation); (4) the potential for eye movements (greater in prolonged visual search displays); (5) the degree of subject knowledge about the attributes of the target prior to display onset (greater in visual search); (6) the number and type of response alternatives (usually larger in texture segmentation); (7) the dependent measures (RT in search vs. accuracy in texture), and (8) the pattern of data taken as evidence for preattentive processing (RT slopes over display size vs. accuracy functions over exposure time). Many of these factors have already been shown to have a significant impact on performance (e.g. Callaghan, 1989; Klein & Farrell, 1989; Wolfe, 1992).

Consequently, the first goal of this study was to compare two tasks that are similar enough so that any discrepancies can be interpreted. These tasks will be tested using a wide range of stimuli that are theoretically relevant to two-stage theories. Both tasks involved two alternative forced-choice RT and displays which remain on until the subject makes a response. The first was standard visual search, in which display size was varied between 2–8–14 items and the target was present in half the displays. The primary measure was the average target-present RT slope, which was used to estimate attentional scanning speed.

The second task was multiple target search (Eriksen, Goettl, St James, & Fournier, 1989; Mordkoff & Egeth, 1993; Mordkoff & Yantis, 1991; Mullin & Egeth, 1988; Townsend & Ashby, 1983). This is similar to standard visual search, in that it also involves detection of target presence. Instead of varying display size, however, the number of targets was varied between 0–1–2–3, while the total number of items was held constant at 24. This makes it somewhat more similar to texture segmentation, both because there is sometimes more than one target in the display, and because there is greater overall spatial density of items. The primary measure here was RT gain, and average decrease in response time that occurred as the number of targets increased from one to three.

If these two search tasks measure the same thing, there should be a strong positive correlation across stimuli between the RT slope in standard search and

RT gain in multiple target search. Furthermore, stimuli with search slopes approaching zero should also yield gains approaching zero. This is because search slopes are presumed to approach zero when targets can be detected in parallel, as if a large number of processors were operating independently at different display locations. However, there is also the possibility that small search slopes might be associated with slightly larger gains, if some processors operating in parallel went to completion faster than others. This pattern might also be expected if there was a floor effect in standard search.

If an attentional spotlight must be moved between items to find targets, then gain would be expected to be much larger than the standard search slope. This is because the effective display size (the number of items to be searched on average before a target is found) decreases radically as the number of targets increases. When there is one target randomly placed in a 24-item display the effective display size is 12; with two targets the effective display size is 6; for three targets the effective display size is 4, assuming serial self-terminating search. For this reason, the multiple target results will also be examined as if they were from a search study in which the display size varied from 4–6–12. If the two tasks are measuring the same thing, their respective slopes should be approximately equal when plotted in this way.

If the standard search slope turns out to be larger than this multiple target slope, then it is possible that standard search slopes are inflated by eye movements that covary with display size (i.e. the total area occupied by items increases with display size in standard search but not in multiple target search). Conversely, if the standard search slope is smaller than the multiple target slope, perhaps the increased density of items there facilitates local item comparisons.

The second, exploratory, goal of this study was to examine the relations between enumeration and search. This comparison is potentially important for both theories of enumeration and theories of vision. The enumeration literature distinguishes between two processes: *Subitizing* is a fast (40–100ms/item) and accurate process specialized for one–four items, whereas counting is a slow (250–350ms/item) and error-prone process that is used for four or more items (Kaufman, Lord, Reese, & Volkmann, 1949; Klahr, 1973). Although there are many theories of enumeration, only the FINST-based theory makes differential predictions about the effects of attention on enumeration (Trick & Pylyshyn, 1994). According to this theory, subitizing is only possible if the information necessary to define the object as a whole, or to distinguish target items to be enumerated from distractors, is available preattentively. If it is not, then the slower counting process must be used for both small and large numbers. Thus, FINST theory predicts that there will be two categories of stimuli in the enumeration tasks: those in which the 1–3 range slope is small and the slope for 5–7 large, and those in which both the 1–3 and 5–7 range slopes are large. None of the other theories, including a pattern-based (Mandler & Shebo, 1982), density-based (Atkinson, Campbell, & Francis, 1976), or short-term memory based (Klahr, 1973) theory can accommodate even selective enumeration of targets in distractors.

Next, consider the relation between search and enumeration. Enumeration is more complex than search in that it involves at least three operations that search does not: Item individuation (singling a particular item out to be enumerated), augmenting a memory counter or running total, and marking the item off as counted (Ullman, 1984). How do these processes fit together with those of search, when subjects are given the task of enumerating items in distractors?

We will start from simple assumptions. There are three possible ways that search and enumeration processes might fit together. One is that enumeration is carried out before targets are distinguished from distractors. We shall call this Enumeration-Before-Definition. In this account, when subjects are asked to enumerate targets amongst distractors they enumerate all the items first, and only then eliminate the items that are not targets. This is a convoluted approach to enumeration, but if subjects were unable to selectively enumerate, as might occur if subjects used only contour density to infer number (e.g. Atkinson et al., 1976), then they would be forced to get their number estimate first, and then modify. This would cause RT overall to be high, because subjects would have to count all the display items first. Moreover, in a display where the total number of items is fixed, RT should decrease as the number of targets increased because there would be fewer subtractions.

A more plausible possibility is that enumeration processes are alternated with those involved in discriminating target items from distractors (Enumeration-During-Definition). In this model, subjects perform multiple searches in order to enumerate. For example, they might find the first item, individuate it, increase the value of the running total, and then mark the item as counted. Then they would find the next target, which would require additional time equal to the remaining display size after one target had been removed, times the target present slope. If the individuation, marking, and incrementing processes required no time, the enumeration slope would be approximately equal to the slope in standard search. However, if these processes required measurable time then the enumeration slope would be larger than the search slope by the same amount. In either case, there should be a strong positive correlation between slopes in search and enumeration tasks with the same stimuli.

A final possibility is that enumeration occurs only after the targets are defined (Enumeration-After-Definition). Each additional item would add one counter-augmentation process to RT, one item individuation process, and one marking process; RTs would increase with the number of target items. However, the search slope would have no place in the enumeration slope in this model. All the detection processes involved in search occur before the enumeration of the items begins. If all types of stimuli were enumerated in this fashion, the correlations between enumeration slopes and search slopes should approach zero across stimuli. The rate at which target items could be found in search would have nothing to do with the subitizing slope, because the subitizing slope originated from processes that occurred after the search. The slope across the number range should also be constant; RT should increase by a constant amount with the number of targets.

In order to keep tasks as similar as possible, a two alternative number discrimination task was used. Subjects pressed one key if there were *n* and another if there were *n+1* target items. Four different discriminations were used: 1/2, 2/3, 7/8, and 8/9. The only difference between this and standard number discrimination was that here subjects were required to enumerate target items in a field of distractors (c.f. Folk, Egeth, & Kwak, 1988; Francolini & Egeth, 1979, 1980). The total number of items in the display was held constant at 24, as in the multiple target task, but the number of targets varied from one to nine depending on the discrimination. The primary measure was enumeration slope, the average increase in RT as the magnitude of the discrimination increased. In fact, two slopes were calculated: the 1–3 slopes was calculated by subtracting the average 1/2 RT from the average 2/3 RT; the 7–9 RT was calculated by subtracting the average 7/8 RT from the average 8/9 RT.

Previous research suggests a relation between attentional processes in search and enumeration slopes, particularly when there are less than four items (Trick & Pylyshyn, 1993, 1994). For this reason, the primary concentration will be on the 1–3 range slopes, though the 7–9 range slopes were also calculated to provide a basis of comparison, and are listed in the last section of the paper. (The 7–9 range slopes were problematic in Experiment 2 because of high error rates.)

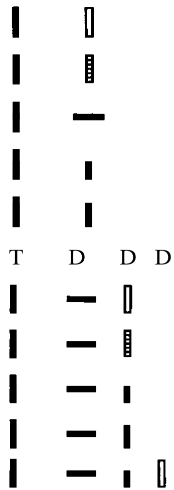
Experiment 1 tested stimuli that differed either in simple feature values or in conjunctions of features. Experiment 2 examined stimuli that differed in their spatial relations between parts and in the scene-based cues of direction of lighting and 3D orientation. Experiment 3 explored stimuli differing in shading, so as to give the impression of convexity versus concavity. Results were analysed in two stages. First, the data from each of the three tasks were analysed separately to ensure adequate power to produce the expected effects in the literature. Second, measures from each task were compared with one other.

EXPERIMENT 1

We designed sets of targets and distractors that differed in simple features and in feature conjunctions, as shown in Table 1. Feature values at more than one level of difficulty were included both because of reports that some conjunctions involving highly discriminable features can be processed very rapidly (Treisman & Sato, 1990; Wolfe et al., 1989) and reports showing that simple feature processing may be quite slow if the difference is subtle (Cohen, 1993; Duncan & Humphreys, 1989; Treisman & Gormican, 1988).

TABLE 1

Stimuli and Attentional Measures (in Milliseconds) for Standard Search, Multiple Target Search, and Number Discrimination Tasks for Experiment 1



		Search Slopes	*Multiple Target Gain*	*Number Discrimination 1–3 Range Slopes*
Features	T D			
1 Easy bright		2.2	1.5	4.9
2 Hard bright		2.8	4.4	35.7
3 Orientation		1.2	9.6	35.1
4 Easy length		3.0	7.7	43.9
5 Hard length		8.1	46.3	101.3
Conjunctions	T D D D			
6 Easy bright × orientation		9.9	19.6	108.1
7 Hard bright × orientation		15.8	24.4	187.3
8 Easy length × orientation		9.0	24.0	146.3
9 Hard length × orientation		17.2	49.9	42.8
10 Triple conjunction:				
Hard length × orientation × easy bright		20.0	31.6	74.0

Note: T = Target; D = Distractor.

Method

Design. As shown in Table 1, the target item was always the same (dark vertical bar), but there were 10 different types of distractors. Throughout this paper, "condition" will refer to the stimulus (the type of targets and distractors), and "task" will refer to one of three methods (standard search, multiple target search, or number discrimination). Conditions 1–5 involved a simple feature difference; Conditions 6–9 involved a double conjunction; and Condition 10 involved a triple conjunction in which each distractor shared two features with the target.

Within each task, Condition (1–10) was analysed as a between-groups factor, while Display Size (2, 8, 14), Target Presence in the standard search task (present, absent), Target Number in the multiple target task (0, 1, 2, 3), and Discrimination in the number discrimination task (1 vs. 2, 2 vs. 3, 7 vs. 8, and 8 vs. 9) were within-subjects factors. The primary dependent measure in all tasks was RT, although accuracy data were collected and analysed to ensure that speed–accuracy trade-offs did not influence results.

Subjects. Subjects were undergraduate students at the University of British Columbia who participated either for partial course credit or payment of $5. Although there were a total of sixty different subjects, only four participated in every condition by task combination. Subjects were not required to participate in more than one session as a policy of the university subject pool. The others performed up to six conditions in one or two of the three tasks. The practice of considering Condition and Task as between-groups factors thus errs on the conservative side for purposes of statistical significance. Moreover, the presence of different subjects in different tasks would also tend to underestimate the correlations between tasks.

Apparatus and Stimuli. The tasks were administered on a Macintosh computer running the VSearch program (Enns, Ochs, & Rensink, 1989). Subjects were seated approximately 50cm from the screen. All displays contained horizontal or vertical bars presented on a medium grey background (one out of two pixels lit). All items fell within a $15° \times 10°$ area of the display. The location of each item was chosen from one of 6×4 possible array positions. The distance between items was approximately 2.5°, although the items were jittered by 0.5° to ensure the items were not colinear.

For every display type, the target item was a $0.23° \times 1.14°$ vertical black bar (no pixels lit). For the Easy Bright conditions the distractors were white (all pixels lit) vertical bars, whereas for Hard Bright conditions the distractors were grey (one out of four pixels lit) vertical bars. For the Orientation condition the distractors were black horizontal bars of the same length as the target. For Easy Length condition the distractors were one-third the length of the target (0.38°)

and for Hard Length condition they were two-thirds the length (0.76°). Distractors in the five remaining conditions were composed of appropriate conjunctions of three stimuli, as shown in Table 1.

In the search tasks, there were either 2, 8, or 14 items on the screen, with half of the displays containing a target on a random basis. In the multiple target task there were always 24 items, with a random half of the displays containing one or more targets. The target present displays were divided evenly, on a random basis, between one, two, and three targets. In the number discrimination task, there were again 24 items in each display and a varying number of target items. Four target size conditions were presented in a counterbalanced order: 1 vs. 2, 2 vs. 3, 7 vs. 8, and 8 vs. 9.

Procedure. Each trial was preceded by a fixation point for 480ms. Displays remained visible until subjects made a response or until 2.8s had elapsed (in search tasks) or 7.7s had elapsed in number discrimination. Subjects pressed one of two computer keys in each task. Immediately after the subject's response (or the time-out), visual feedback was presented at the fixation point for 480ms (a plus or minus sign).

Testing in the search tasks consisted of three blocks of 30 trials after one block of practice. Number discrimination consisted of four blocks of 48 trials, one for each of the four discriminations (1/2, 2/3, 7/8, and 8/9), with practice given on each particular discrimination immediately before the test trials. For example, subjects would be given the practice trials for the 3/4 discrimination immediately before being tested in that condition; then they would be given practice for another discrimination before being tested in it. Sessions lasted approximately 30 minutes.

Results

Correct mean RT is shown in Figure 1 (Visual Search), Figure 2 (Multiple Target Search), and Figure 3 (Number Discrimination). A convenient summary of the primary measure in each task is shown in Table 1. Interesting significant effects in a preliminary ANOVA were followed up with Fisher's LSD tests (protected *t*-tests).

Visual Search. All main effects and interactions were significant at $p < .01$: Stimulus condition, $F(9, 140) = 10.4$, MSE = 102,276; target presence and target presence × condition, $F(1, 140) = 181.6$, $F(9, 140) = 11.9$, MSE = 8144; display size and display size × condition, $F(2, 280) = 225.0$ and $F(18, 280) = 16.5$, MSE = 5664; target presence × display size and target presence × display size × condition, $F(2, 280) = 21.8$ and $F(18, 280) = 7.2$, MSE = 2197. In general, this task produced results consistent with two-stage theory in that feature conditions tended toward smaller RT slopes than conjunction conditions.

(a)

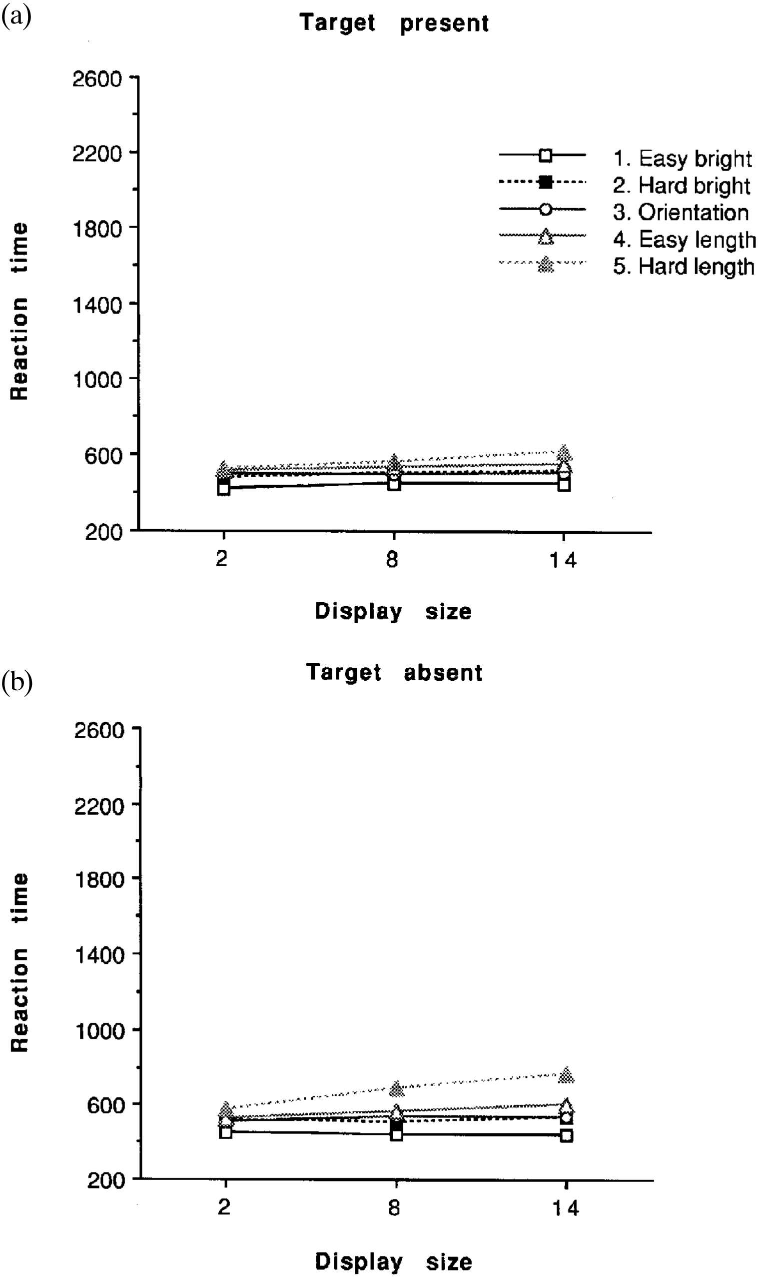


FIG. 1. Response times in the standard visual search task in Experiment 1; Conditions 1–5, target (a) present, (b) absent; Conditions 6–10, target (c) present, (d) absent.

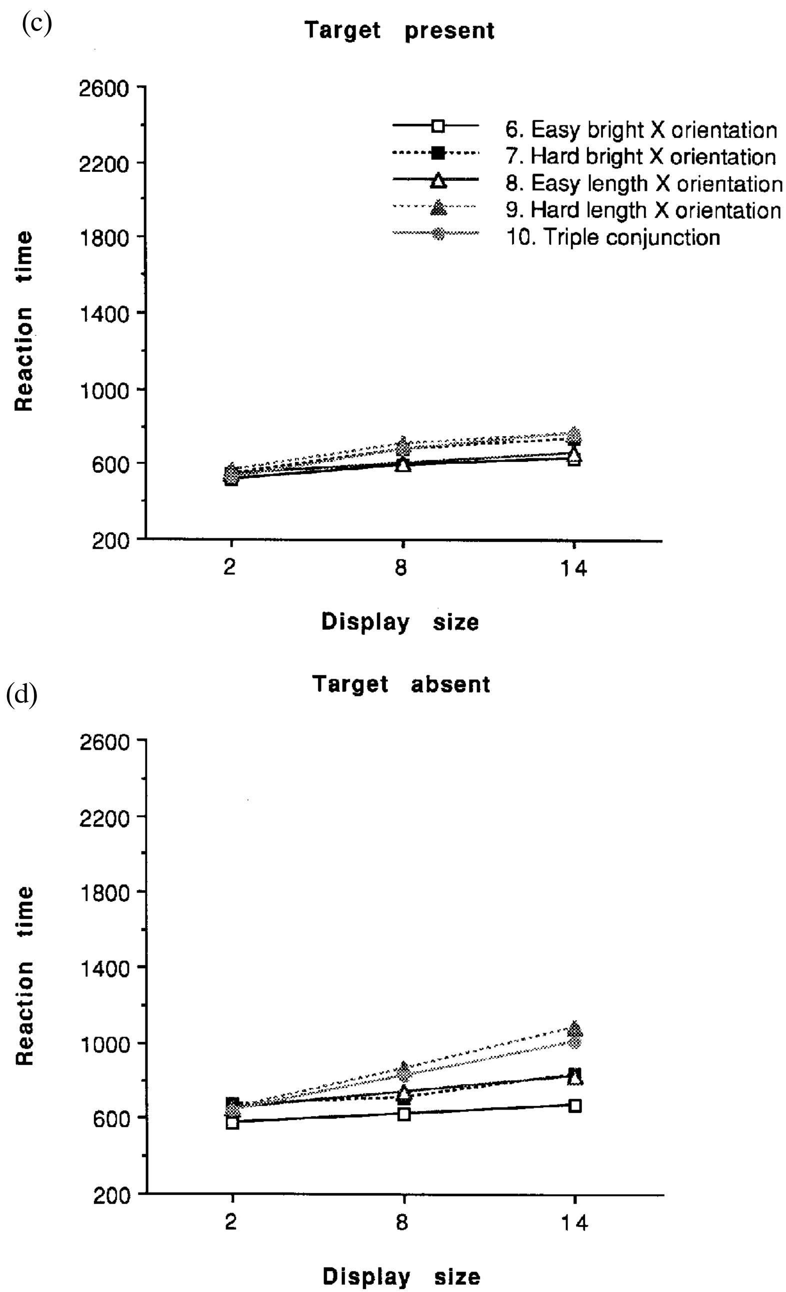


FIG. 1. Continued.

(a)

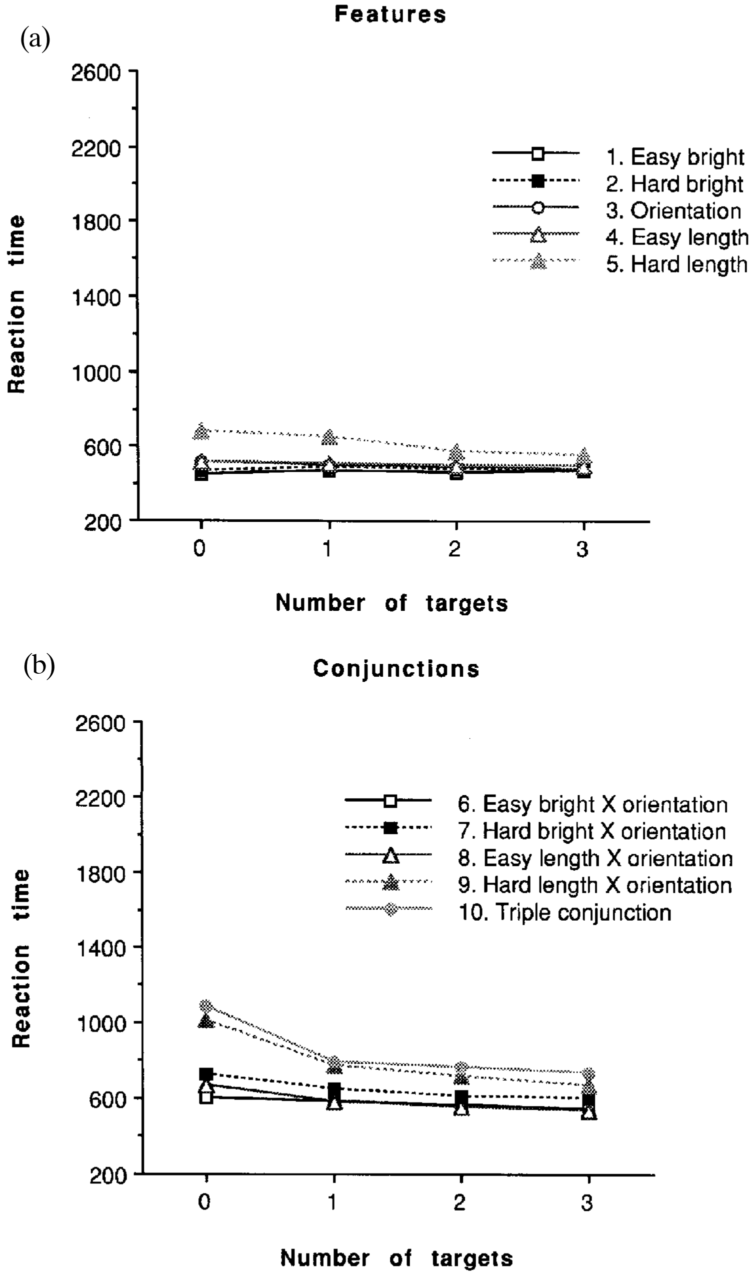
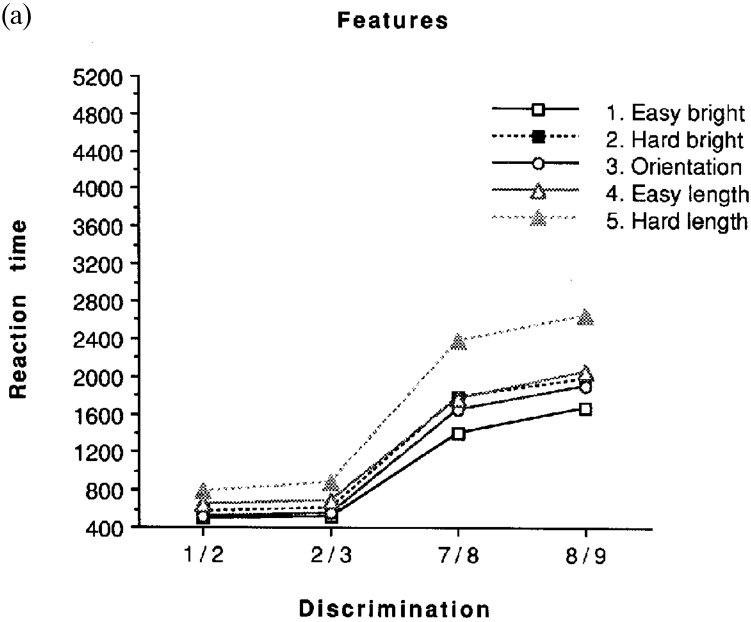


FIG. 2. Response times in the multiple target search task in Experiment 1; (a) Features (Conditions 1–5), (b) Conjunctions (Conditions 6–10).

(a)



(b)

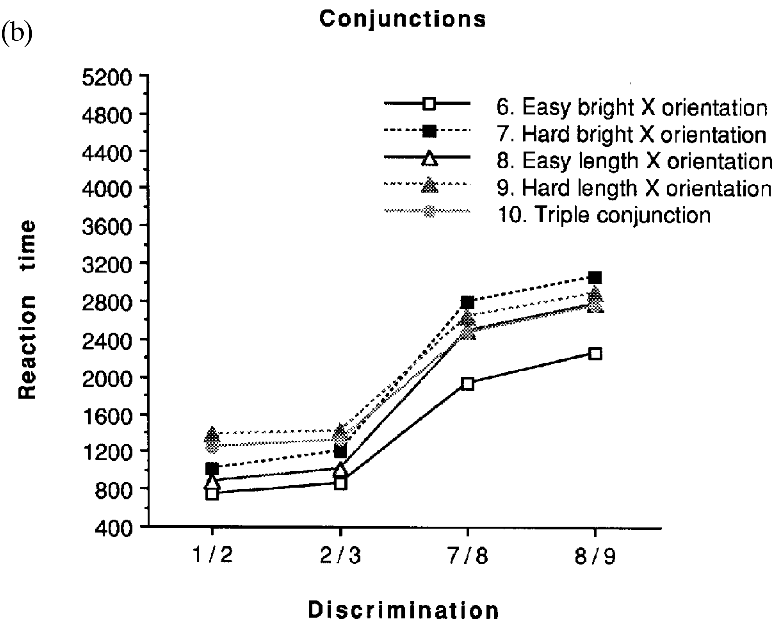


FIG. 3. Response times in the number discrimination task in Experiment 1; (a) Features (Conditions 1–5), (b) Conjunctions (Conditions 6–10).

However, there were also some interesting subtleties, as can be seen in Table 1. For instance, although there was little difference between easy and hard conditions when simple feature differences were examined in isolation (see Condition 1 vs. 2 and Condition 4 vs. 5) the differences became more apparent when conjoined with orientation (see Condition 6 vs. 7 and Condition 8 vs. 9).

Errors were very infrequent, as shown in Table 2. Most importantly, they mirrored the RT data. Errors increased with display size, the highest error rates were found in the most difficult search conditions, and across conditions, RT slopes were positively correlated with errors, $r(8) = +0.79$. Overall, there was

TABLE 2
Error Rates for Standard Search, Multiple Target Search, and Number Discrimination for Experiment 1 (Percentage Error)

	Standard Search	*Multiple Target Search*	*Number Discrimination*	
			1–3 Range	*7–9 Range*
1 Easy bright				
Present	3	4	3	7
Absent	2	2		
2 Hard bright				
Present	2	3	2	6
Absent	2	2		
3 Orientation				
Present	3	4	3	8
Absent	2	2		
4 Easy length				
Present	2	4	3	7
Absent	1	1		
5 Hard length				
Present	4	6	5	13
Absent	3	2		
6 Easy bright × orientation				
Present	5	5	7	12
Absent	1	1		
7 Hard bright × orientation				
Present	5	7	6	11
Absent	1	2		
8 Easy length × orientation				
Present	3	4	3	8
Absent	2	1		
9 Hard length × orientation				
Present	5	8	9	14
Absent	2	1		
10 Triple conjunction: Hard length × orientation × easy bright				
Present	7	8	5	13
Absent	2	1		

no evidence of a speed–accuracy trade-off; there was almost no correlation between RT and error rate *per se*, $r(898) = + 0.01$.

Multiple Target Search. Once again, all main effects and interactions were significant at $p < .01$: Stimulus condition, $F(9, 140) = 13.4$, MSE = 34,994; number of targets, $F(2, 280) = 47.1$; and their interaction, $F(18, 280) = 2.9$, MSE = 1613). However, as shown in Table 1, the RT gain measure did not produce exactly the same pattern as the RT slope measure in standard search. In particular, Hard Length (Condition 5) was more similar to the most difficult of the conjunctions (Condition 9) than to the other simple features (Conditions 1–4). Otherwise, the simple feature conditions were easiest, followed by conjunction conditions, with the conjunction of Hard Length × Orientation being the most difficult of all.

Subjects averaged 5.2% errors, with the error pattern generally mirroring that for RT, as shown in Table 2. There was a correlation between RT gain and errors of $r(8) = + 0.82$ across conditions, but overall, the correlation between RT and error rate was very small, $r(598) = + 0.10$.

Number Discrimination. Feature conditions again produced generally faster RTs than conjunction conditions, and all main effects and interactions were significant at $p < .01$: Stimulus condition, $F(9, 140) = 10.6$, MSE = 852,827; discrimination and discrimination × condition: $F(3, 420) = 726.2$, $F(27, 420) = 2.4$, MSE = 137,599. None the less, the proposed dichotomy between these two types of condition was even less pronounced in this task than in the previous two. Consider the slope measure shown in Table 1, which was calculated by subtracting the average RT in the smaller target size condition (1 vs. 2) from that in the larger size condition (2 vs. 3). The results show a clear gradient of difficulty even within the feature conditions (1–5) that was not apparent in standard visual search or in multiple target search. Indeed, the overlap in performance levels between feature and conjunctions conditions is so great that one of the conjunction conditions (9) was easier than two of the simple feature conditions (4 and 5).

Errors averaged 7.5% and again mirrored the RT data, as shown in Table 2. RT slope and errors correlated $r(8) = + 0.28$ in the 1–3 range of target size and $r(8) = + 0.25$ in the 7–9 range. Overall RT and error rates correlated $r(598) = + 0.14$ in the 1–3 range and $r(598) = + 0.04$ in the 7–9 range.

Overview. At a very coarse level of analysis, each of the three tasks yielded results consistent with two-stage theory—simple feature conditions were generally easier than feature conjunction conditions. One way to measure this overall consistency is to consider the correlation between the attention measures in the three tasks. Across the 10 conditions, search RT slope and multiple target RT gain were strongly correlated, $r(8) = + 0.73$, $p < .05$, whereas the correlations involving the 1–3 range number discrimination slopes were smaller but still positive (search RT slope: $r(8) = +0.49, p < .1$; multiple target RT gain: $r(8) = +0.36, p < .1$).

EXPERIMENT 2

The scene-based attributes of direction of lighting and 3D orientation can produce "pop out" in visual search (Aks & Enns, 1992; Enns & Rensink, 1990, 1991). The targets in these studies differed from distractors only by virtue of the spatial relations that existed among simple elements such as lines and 2D shapes. None the less, because they "popped out", these stimuli challenge the original version of the two-stage theory. It is not clear whether this finding generalizes to other tasks, however. Indeed, preliminary studies suggest that scene-based attributes may not produce effortless texture segmentation (Enns & Rensink, 1993). In the present experiment we compared search for direction of lighting and 3D orientation in standard visual search, multiple target search, and number discrimination.

Method

Subjects. A total of 47 subjects were tested, with some serving in more than one task and condition. Only two participated in all conditions of the two search tasks. The remainder served in all conditions of only one of the three tasks. Thus, 13 served in the search task, 12 in the multiple target task, and 14 in the number discrimination task.

Stimuli. The stimuli are shown in Table 3. To test the lighting feature (Condition 11), targets were cubes shaded to look as if they were lit from the lower right; distractors were same-oriented cubes shaded to look as if they were lit from the upper left. To test Orientation + Lighting (Condition 12) the items were again shaded cubes, but now the target was oriented upward (bottom-view) and the distractors downward (top-view).

To test orientation in the absence of associated shading (Condition 13) items contained the same geometry as Condition 12, but all shading was removed. In a previous study, this target was insufficiently distinct to produce search slopes below the 10ms/item criterion (Enns & Rensink, 1991).

The remaining three conditions involved items that had similar differences in the spatial arrangement of elements but did not evoke a 3D interpretation. The Lighting control (Condition 14) consisted of targets and distractors differed in the luminance relations between the elemental shapes. In the Orientation + Lighting control (Condition 15) the spatial relations between the shapes were varied, and in the Cube orientation control (Condition 16) the orientation of an interior Y-junction was varied.

TABLE 3

Stimuli and Attentional Measures (in Milliseconds) for Standard Search, Multiple Target Search, and Number Discrimination Tasks for Experiment 2

			Search Slopes	Multiple Target Gain	Number Discrimination 1–3 Range Slopes
3D STIMULI THAT POP OUT	T	D			
11 Lighting			11.7	58.0	187.0
12 Orientation + lighting			10.1	51.6	652.5
STIMULI THAT DO NOT POP OUT	T	D			
13 Cube orientation			45.4	90.6	640.2
14 Lighting control			22.8	126.0	400.1
15 Orientation + lighting control			17.4	82.8	552.4
16 Cube orientation control			68.2	139.8	515.0

Note: T = target; D = distractor.

All search items subtended approximately 1.4°. Those in Conditions 13 and 16 were presented on a white background; all others were on a grey background. Otherwise, display conditions were identical to those in the previous experiment.

Procedure. The procedure was the same as in Experiment 1, except that the maximal display duration was increased to 4s for standard and multiple target search because search was more difficult. (Display duration was already at the maximal 7.7s in number discrimination.)

Results

Mean correct RT are presented in Figure 4 (standard search), Figure 5 (multiple target search), and Figure 6 (number discrimination). Summaries of the attentional measures are presented in Table 3.

Visual Search. Overall, RTs were much longer than in the first experiment. All main effects and interactions were significant at $p < .01$: Stimulus condition, $F(5, 72) = 21.5$, MSE = 280,489; target presence and target presence × condition, $F(1, 72) = 224.8$, $F(5, 72) = 8.1$, MSE = 33,044; display size and display size × condition, $F(2, 144) = 323.5$, and $F(10, 144) = 26.0$, MSE = 33,337; target presence × display size and target presence × display size × condition, $F(2, 144) = 102.3$, $F(10, 144) = 5.4$, MSE = 12,061. Conditions 11 and 12 produced significantly lower search slopes than the rest ($p < .05$), as predicted.

Error rates are shown in Table 4. The error rate was very low, 3.5% overall, but mirrored the pattern in the RT data. RT slopes and errors were strongly correlated, $r(4) = +0.97$, $p < .05$. Overall, there was no evidence of a speed–accuracy trade-off with raw RT and error correlated at only $r(466) = +0.19$.

Multiple Target Search. The two main effects were significant at $p < .01$, though the interaction was not: Condition, $F(5, 66) = 36.9$, MSE = 139,080; number of targets and number of targets × condition, $F(2, 132) = 35.3$, $F(10, 132) = 1.1$, MSE = 18,134. In general, gains were much higher in this experiment than in Experiment 1, even for the two conditions that produced pop out (Conditions 11 and 12). They produced gains as large as even the most difficult conjunction in Experiment 1. Nonetheless, they had significantly lower gains than the two slowest conditions ($p < .05$) in this experiment (Conditions 13 and 16), though they did not differ significantly from the other conditions.

The average error rate was 7.4% as shown in Table 4. Accuracy analyses mirrored the RT analyses, with high gains associated with large numbers of errors. The correlation between gain and error rate for one to three targets was $r(4) = +0.64$, and the correlation between error rate and RT was $r(286) = +0.28$.

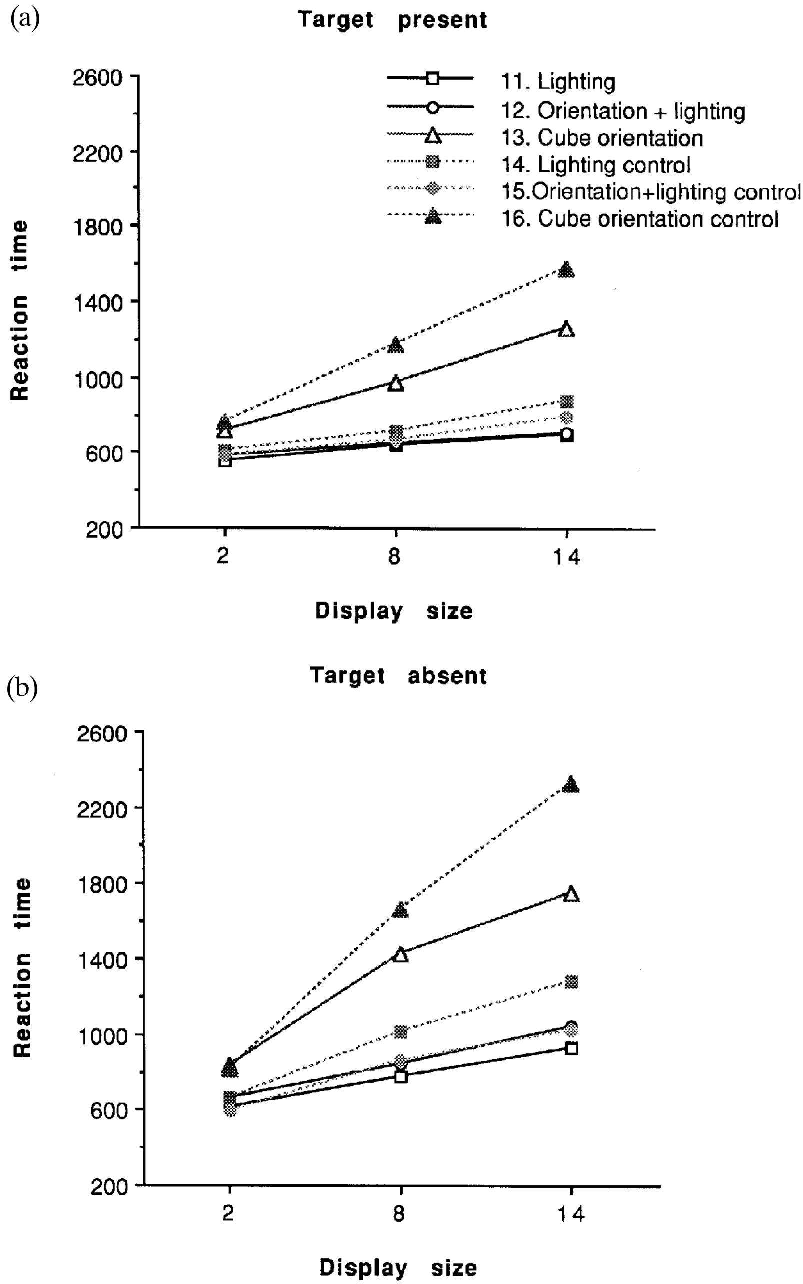


FIG. 4. Response times in the standard visual search task in Experiment 2; (a) target present, (b) target absent (Conditions 11–16).

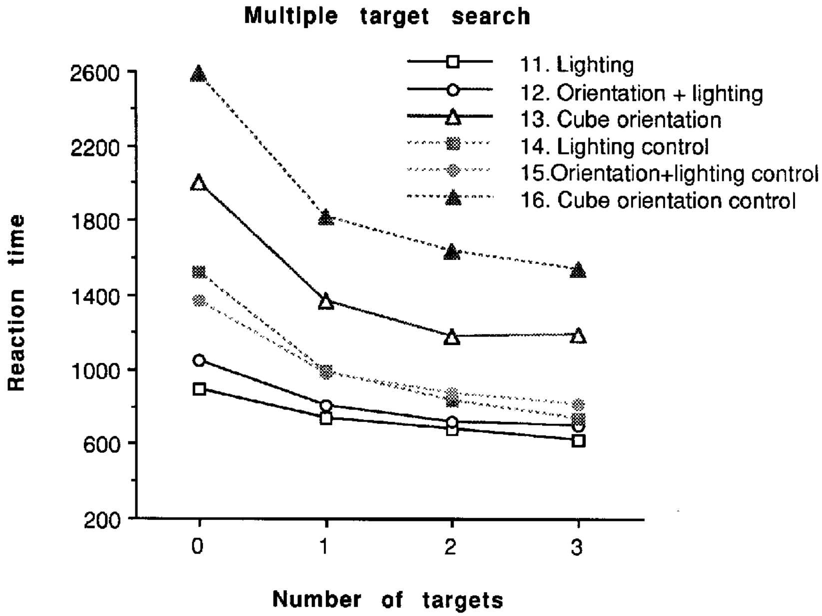


FIG. 5. Response times in the multiple target search task in Experiment 2 (Conditions 11–16).

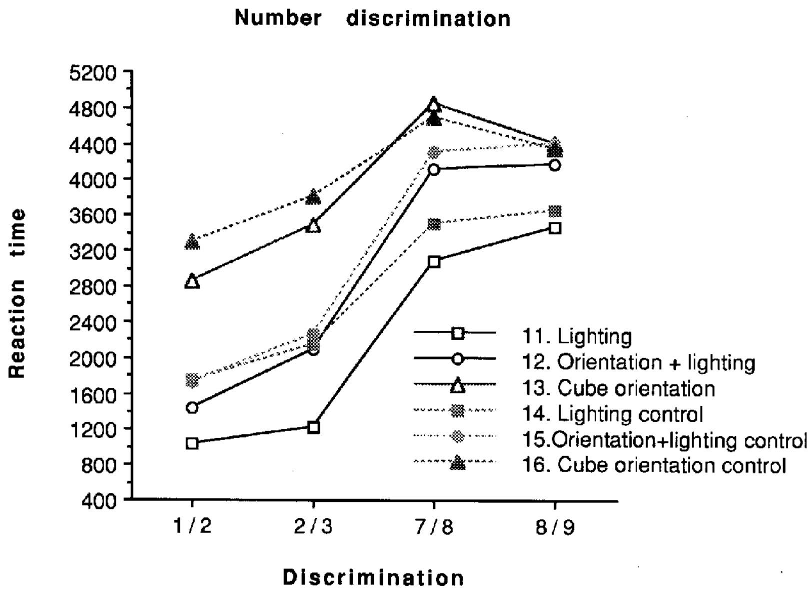


FIG. 6. Response times in the number discrimination task in Experiment 2 (Conditions 11–16).

TABLE 4
Error Rates for Standard Search, Multiple Target Search, and Number Discrimination for Experiment 2 (Percentage Error)

	Standard Search	*Multiple Target Search*	*Number Discrimination* 1–3 Range	*Number Discrimination* 7–9 Range
11 Lighting				
Present	4	6	5	13
Absent	1	1		
12 Orientation + lighting				
Present	3	4	11	28
Absent	1	3		
13 Cube orientation				
Present	8	15	20	34
Absent	3	6		
14 Lighting control				
Present	5	5	9	14
Absent	1	1		
15 Orientation + lighting control				
Present	3	5	7	17
Absent	1	1		
16 Cube orientation control				
Present	11	21	23	39
Absent	2	8		

Number Discrimination. All main effects and interactions were significant at $p < .01$: Stimulus condition, $F(5, 78) = 5.6$, MSE = 4,816,825; number discrimination and number discrimination × condition, $F(3, 234) = 291.8$, $F(15, 234) = 5.5$, MSE = 333,039. Notice that RTs were much higher in this experiment than in the first. Although Conditions 11 and 12 produced modest search slopes, 1/2 discrimination RTs were in excess of 1s. Nevertheless, these conditions did have lower RTs in the 1/2 range than the other conditions ($p < .05$), as predicted. It was also predicted that stimuli with a 3D interpretation would be processed more rapidly than their controls. Although this did occur in trend, the difference was not always significant. Subjects were significantly faster for Lighting than for the Lighting control (Conditions 11 and 14), but there was no significant difference between Orientation + Lighting and the Orientation + Lighting control (Conditions 12 and 15). Similarly, the RTs for Cube orientation and Cube orientation control (Conditions 13 and 16) were not significantly different.

The enumeration slopes were unusual. Lighting (Condition 11) was the only one with RT functions similar to those in Experiment 1. Even then, the RT slope in the 1–3 range was as high as those for the most difficult conjunctions. In all other conditions, the 1–3 range slope was in excess of 400ms, and the 7–9 range slopes were low and sometimes even negative (51, –435, 144, 105, and –341ms/item for Conditions 12–16, respectively). Because these low slopes were strongly related to a high error rates, $r(4) = -0.91$, it is probable that subjects were trading speed for accuracy in the 7–9 range. In contrast, in the 1–3 range low slopes were associated with low error rates, $r(4) = +0.50$, so speed–accuracy trade-offs seem less likely.

The error rate was substantially higher in this study at 18.3%, and especially exaggerated in the 7–9 range in Conditions 12, 13, and 16, as shown in Table 4. Overall, error rate and RT were uncorrelated, $r(334) = +0.09$ in the 1–3 range, $r(334) = +0.13$ in the 7–9 range.

Overview. As in Experiment 1, there were positive correlations among the attention measures in the three tasks: Search slope and multiple target gain, $r(4) = +0.76$, $p < .05$; search slope and number discrimination slope, $r(4) = +0.26$, $p < .1$; multiple target gain and number discrimination slope, $r(4) = +0.04$, $p < .1$. However, the negligible correlations involving number discrimination make it clear that there were also larger discrepancies between tasks.

In summary, although direction of lighting and 3D orientation seem to behave like simple features in standard visual search, they don't behave that way in multiple target search or number discrimination tasks. In fact, the results from these other tasks are consistent with Enns and Rensink's (1993) finding that texture segmentation takes considerable time when the display items differ only in the attributes of lighting direction and/or 3D orientation.

EXPERIMENT 3

Subjects are inclined to see disks containing linear luminance gradients as surface convexities (if the gradient runs from dark at bottom to light at the top) and surface concavities (if the gradient runs from light at bottom to dark at the top). These differences are distinctive enough to produce rapid texture segmentation (Ramachandran, 1988) and pop-out visual search (Aks & Enns, 1992; Kleffner & Ramachandran, 1992). However, there is also an interesting asymmetry in the search results for naive subjects: Bottom-lit targets tend to pop out from top-lit distractors, whereas top-lit targets against bottom-lit distractors do not (Kleffner & Ramachandran, 1992). This suggests that the visual system is able to organize scenes more rapidly when the light is from overhead.

Thus, unlike the stimuli used in Experiment 2, shaded disk stimuli have been shown to produce both rapid visual search and effortless texture segmentation. We wanted to find out whether these stimuli would also yield consistent results between search and number discrimination.

Method

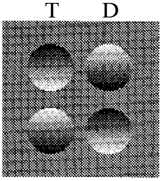
Subjects. A total of 29 subjects were tested, with some serving in more than one task and condition. Only one participated in all conditions and tasks. Most of the remaining subjects served in both conditions of at least one task. Thus, 12 served in the search task, 14 in the multiple target task, and 16 in the number discrimination task.

Design. The two search tasks each had one between-subjects factor (condition), while the number discrimination task was completely within-subjects. Order of condition was counterbalanced across two sessions of testing. For number discrimination, subjects performed each of the eight number discriminations (1/2, 2/3, 3/4, 4/5, 5/6, 6/7, 7/8, 8/9) in a Latin-square counterbalanced order, with the constraint that they were not tested with conflicting mappings between number and response key in immediate succession.

Stimuli. The items for Bottom-lit and Top-lit target conditions (Conditions 17 and 18) are shown in Table 5. Each item subtended 1.45°. The parameters were slightly different than in the previous experiments: (1) the display occupied 16.5 × 12.9°; (2) the minimal distance between items was 2.8° horizontal and 2.6° vertical, and (3) items were chosen from a 6 × 5 array in search, and for the number discrimination and multiple target tasks there were 30 rather than 24 items in a display. Items were presented on a grey background.

Procedure. The procedure was otherwise the same as in previous experiments.

TABLE 5
Stimuli and Attentional Measures (in Milliseconds) for Standard Search, Multiple Target Search, and Number Discrimination Tasks for Experiment 3

	T D	*Search Slopes*	*Multiple Target Gain*	*Number Discrimination 1–3 Range Slopes*
17 Bottom-lit targets		2.8	2.3	122.2
18 Top-lit targets		14.0	40.7	–214.4

Note: T = target; D = distractor.

Results

Correct mean RT are presented in Figure 7 (standard search), Figure 8 (multiple target search), and Figure 9 (number discrimination). The attentional measures are listed in Table 5.

Visual Search. All main effects and interactions were significant at $p < .05$: Stimulus condition, $F(1, 22) = 5.4$, MSE = 427,763; target presence and target presence × condition, $F(1, 22) = 18.9$, $F(1, 22) = 7.6$, MSE = 96,561; display size and display size × condition, $F(2, 44) = 22.6$, $F(2, 44) = 10.5$, MSE = 23,082; target presence × display size and target presence × display size × condition, $F(2, 44) = 14.4$, $F(2, 44) = 6.6$, MSE = 10,088. As predicted, bottom-lit targets produced slopes less than 10ms per item, whereas the top-lit ones were significantly larger ($p < .01$).

Error rates are listed in Table 6. Overall, the error rate was 2.2% and there was little evidence of a speed–accuracy trade-off, $r(142) = + 0.02$.

Multiple Target Search. Stimulus condition had a significant effect, $F(1, 26) = 11.5$, $p < .01$, MSE = 102,248. There was a marginal effect of the number of targets, and the condition × number of targets interaction was not significant, $F(2, 52) = 2.7$, $p = .08$; $F(2, 52) = 1.7$, $p < .1$, MSE = 6586. Thus,

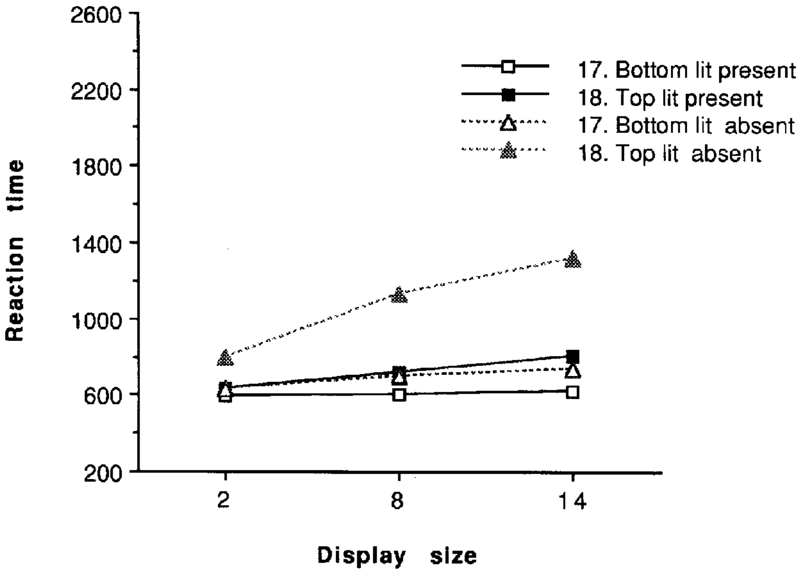


FIG. 7. Response times in the standard visual search task in Experiment 3 (Conditions 17–18).

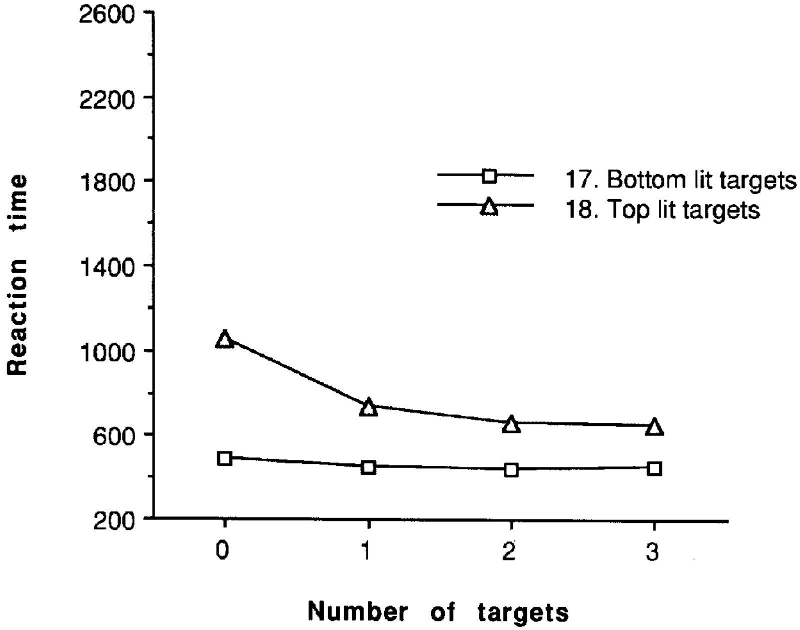


FIG. 8. Response times in the multiple target search task in Experiment 3 (Conditions 17–18).

despite a 40ms difference in gain between bottom- and top-lit targets, this difference was not significant, $F(1, 26) = 1.9$, $p < .1$, MSE = 5383.

The overall error rate was low (3.9%), as shown in Table 6. RT and error rate did not correlate strongly, $r(110) = +0.11$. There was the usual decrease in errors as the number of targets increased from one–three for both target types.

TABLE 6
Error Rates for Standard Search, Multiple Target Search, and Number Discrimination for Experiment 3 (Percentage Error)

	Standard Search	Multiple Target Search	Number Discrimination	
			1–3 Range	*7–9 Range*
17 Bottom-lit targets				
Present	3	5	2	11
Absent	1	2		
18 Top-lit targets				
Present	3	4	6	8
Absent	3	2		

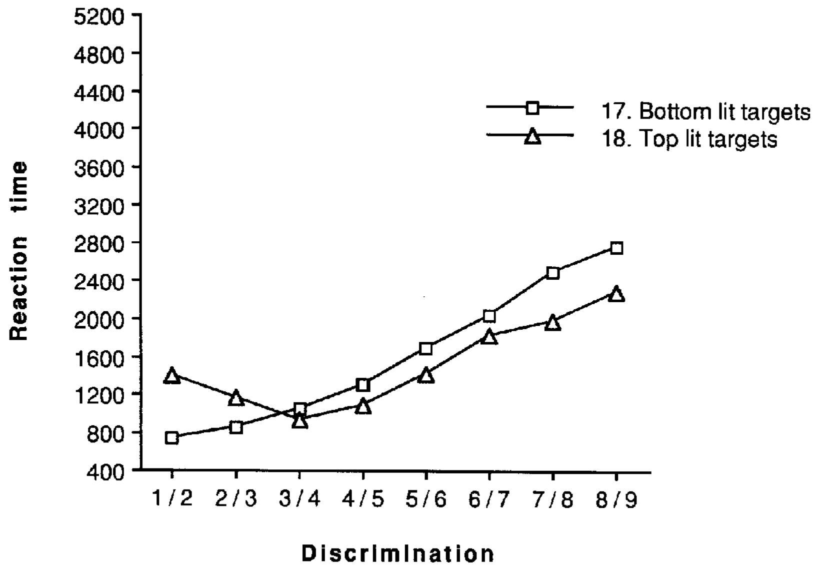


FIG. 9. Response times in the number discrimination task in Experiment 3 (Conditions 17–18).

Number Discrimination. There was no overall difference between the bottom- and top-lit targets, $F(1, 15) = 1.1$, $p < .05$, MSE = 686,988, but there was the usual increase in RT with number of items, $F(7, 105) = 100.6$, and a significant interaction of condition × number of items, $F(7, 105) = 11.1$, $p < .01$, MSE = 114,114. As shown in Figure 9, the enumeration RT for the Bottom-lit targets were comparable to those from difficult feature conditions in Experiment 1, at around 750ms. Also, the 1–3 range slopes for the Bottom-lit targets seemed to be similar to a difficult feature or an easy conjunction. In contrast, however, RT for Top-lit targets started at over 1s for the 1/2 discrimination, and actually dropped as the number of items in the discrimination increased, reaching the lowest point at the 3/4 discrimination. This created a negative slope in the 1–3 range. Although the increase of RT with the number of items varied considerably as a function of condition, there was only a marginal interaction between discrimination and condition, $F(1, 15) = 3.2$, $p = .09$, MSE = 184,619. There was also no overall effect of condition on slopes, $F(1, 15) = 1.2$, $p > .05$, MSE = 270,587.

The reason the condition × discrimination interaction was so weak is that there were two different patterns of response in the top-lit condition, as shown in Figure 10. Six of the sixteen subjects produced the standard increase in RT with the number of items. The remaining 10 subjects gave the function its

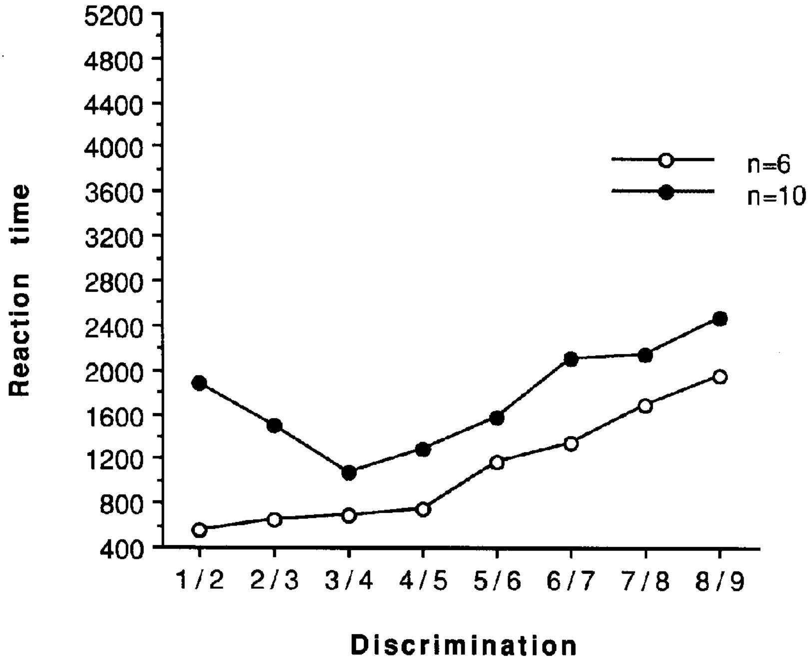


FIG. 10. Individual differences between subjects in the number discrimination task for top-lit targets.

curvilinearity. The bases for individual differences were not clear, since the two groups of subjects did not differ noticeably in their gender composition, their accumulated experience with RT tasks, or in the order in which they participated in the conditions. It is possible that two groups somehow represented the task differently to themselves (e.g. searching for top-lit targets in bottom-lit distractors, vs. looking for spheres in a background of indentations) but this did not seem to cause any differences in the way they enumerated bottom-lit targets. The 10 subjects who produced the curvilinear pattern were slightly more error prone in all but the 8/9 discrimination in the top-lit condition, but the overall difference in accuracy was only 3%.

Subjects tended to make more error for the top-lit targets in the 1–3 range and bottom-lit targets in the 7–9 range. However, this difference was slight, as shown in Table 4. In general, the error rate was low in this study (7.2%), which is in line with number discrimination in Experiment 1. The correlation between error rate and RT was $r(510) = +0.31$, which suggests speed–accuracy trade-offs were not a problem.

We had expected the three tasks would produce results consistent with earlier texture segmentation and visual search studies (Kleffner & Ramachandran, 1992; Ramachandran, 1988). This did occur for the Bottom-lit targets

(Condition 17) in the two search tasks. However, the number discrimination slopes were slightly higher than expected for stimuli that produce rapid texture segmentation. The pattern for Top-lit targets (Condition 18) was completely unforeseen. For most subjects, there was a decrease in RT with the number of targets, until four, and then an increase thereafter.

GENERAL RESULTS AND DISCUSSION

Comparison of Standard and Multiple Target Search

The time required to find one target was strongly correlated across stimuli for standard search (RT to target-present on 14 item displays) and multiple target search (RT to one-target present on 24 item displays), $r(16) = +0.98$, $p < .05$. Moreover, RT slopes and RT gain in these two tasks were highly correlated across stimuli, $r(16) = +0.83$, $p < .05$, which suggests that the tasks reflect similar search processes.

Nonetheless, the RT slopes in standard search were not exactly equal to the RT gains in multiple target search. The standard search slope was always smaller, sometimes by a large amount. Indeed, most of the conditions can be clustered into two categories. The first involves conditions in which the gain exceeded the standard visual search RT slope by 15ms or less. The clearest examples are conditions in which the targets contain simple salient features: Brightness, orientation, or large differences in length (Conditions 1–4) and the easier of the two shape-from-shading differences (Condition 17). Nearer to the boundary of this category were the most difficult conjunctions of orientation, brightness, and large differences in length (Condition 6, 7, 8, 10). These small differences between the standard search slope and gain are not too difficult to explain. A slightly larger RT gain than RT slope could reflect nothing more than a floor effect in the standard search task. Or, it might be that parallel processors indeed were involved in search, but some went to completion faster than others, giving the multiple target task greater sensitivity to this difference.

In the second category, RT gain exceeded the standard search slope by 30–100ms. This included conditions in which the targets and distractors differed by only a small amount in length (Condition 5), by a conjunction of difficult length and orientation (Condition 9), by spatial relations between parts (Conditions 11–16) and by the more difficult of the shape-from-shading differences (Condition 18). These results are consistent with the movement of an attentional focus from item to item. Specifically, increasing the number of targets in the multiple search task has the effect of radically decreasing the number of items that have to be inspected (i.e. the effective display size increases from 4–6–12 as the number of targets decreases from 3–1). When multiple target slopes were plotted this way, it is apparent that the multiple target slopes were usually lower or approximately equal to the standard visual search slopes, as shown in Table 7. Analysis of variance revealed that standard search slopes were significantly larger than these multiple target slopes, though the difference was not large, M = 15.2ms/item vs. M = 10.4ms/item, $F(1, 466) = 15.1$, $p < .01$, MSE = 158. There was also an interaction of condition × task, $F(17, 466) = 4.1$, $p < .01$, MSE = 158, with the largest differences coinciding with the largest slopes. Overall, then, the two types of search seemed to produce consistent results, although the multiple target task appeared to be the more sensitive of the two. This may reflect floor effect limitations, which are inherent in standard visual search but absent in multiple target search.

Exploration of Number Discrimination

This study tested a larger variety of stimuli than any previous enumeration study, and as such, it can help inform theories of enumeration. First, the data demonstrate again that subjects can selectively enumerate target items in a set of distractors (Trick & Pylyshyn, 1993, 1994), a finding that cannot be accommodated by theories based on overall density (Atkinson et al., 1976), configurational pattern (Mandler & Shebo, 1982), or short-term memory (Klahr, 1973). Such theories underestimate the flexibility of human enumeration processes and are limited in their generality.

TABLE 7
Comparison of Relative Number Discrimination Slope with Standard Visual Search RT Slope, and Multiple Target Slope (Given Effective Display Sizes of 4–12 Items)

	Standard Visual Search Slope	*Multiple Target Search Slope*	*Number Discrimination Slope (1–3)*
1 Easy bright	2.2	0.4	Very low
2 Hard bright	2.8	1.1	Low
3 Orientation	1.2	2.4	Low
4 Easy length	3.0	1.9	Low
5 Hard length	8.1	11.6	Medium
6 Easy bright × orientation	9.9	4.9	Medium
7 Hard bright × orientation	15.8	6.1	Medium
8 Easy length × orientation	9.0	6.0	Medium
9 Hard length × orientation	17.2	12.5	Low
10 Triple conjunction:			
Hard length × orientation × easy bright	20.0	7.9	Intermediate–Low
11 Lighting	11.7	14.5	Medium
12 Orientation + lighting	10.1	12.9	High
13 Cube orientation	45.4	22.7	High
14 Lighting control	22.8	31.5	High
15 Orientation + lighting control	17.4	20.7	High
16 Cube orientation control	68.2	34.9	High
17 Bottom-lit targets	2.8	0.6	Medium
18 Top-lit targets	14.0	10.1	Large Negative

Because these theories have no mechanism for enumerating target items among distractors, they cannot explain why the similarity relations between targets and distractors affect enumeration. In the present study, there was a wide range of enumeration slopes across all conditions, even within the 1–3 range, from –214ms/item (subjects were faster to enumerate large numbers of items than small) to 652ms/item, $F(17, 248) = 11.8$, $p < .01$, MSE = 73,370. This can only be explained by a theory that takes into account the critical role of preattentive and attentive processes, as proposed by Trick and Pylyshyn (1993, 1994).

For the stimuli in the present study, Trick and Pylyshyn (1993) would predict two clusters: Those in which the 1–3 range slopes were low and those in which they were relatively high. As shown in Table 7, the slopes in this study really fell into four categories. In the first were stimuli with small positive slopes (~40ms/item or less), including easy features (Conditions 1–4), and the conjunction of Hard Length × Orientation (Condition 9). The most extreme example was Easy Bright (Condition 1), for which the slope approached zero (not noticeably different from the search slope for that condition). Given that the process of individuating items and finding a number name normally requires a certain amount of time (Folk et al., 1988; Trick & Pylyshyn, 1994), it is possible that subjects were not truly enumerating these stimuli, but instead basing their discrimination on a global difference between displays (brighter = n/darker = n+1). Notice that when the brightness difference between targets and distractors was more subtle (e.g. Condition 2), the enumeration slope re-emerged. Moreover, when there were 7–9 items in Condition 1, there was a robust number discrimination slope (284ms/item). The other conditions that fell within this category had slopes close to 40ms/item in the 1–3 range. With the exception of Condition 9, they also showed pop out in standard search. The Triple conjunction (Condition 10) had an enumeration slope higher than this first cluster, but lower than the second, so it was termed intermediate–low in Table 7.

In the second cluster, 1–3 range slopes were 100–200ms/item. The Hard Length feature (Condition 5), various conjunctions (Conditions 6–8), and direction of lighting (Condition 11, 17) fell within this cluster.

The third category consisted of conditions with extremely high 1–3 range slopes, in excess of 400ms/item. This included targets defined by spatial relations (Conditions 12–16). The very large slopes may have resulted because enumerating different items (which requires item individuation and marking) requires exactly the same resources as computing the spatial relations necessary to discriminate targets and distractors. Thus, finding whether each item was a target or distractor may have interfered with the process of singling out items to be enumerated, or remembering which items had already been enumerated.

Finally, there was one unusual case (Condition 18) for which there was a large negative slope in the 1–3 range for most subjects. The complexity of these results is beyond the power of any of present theories of enumeration, or for that matter, any theory of preattention.

Relations between Enumeration and Search

There was a very strong correlation between the average RT to discriminate one from two targets in number discrimination and the RT to find one target in standard search, $r(16) = +0.97$, $p < .01$, and in multiple search, $r(16) = +.98$, $p < .01$. Nonetheless, the more important relation was the one between the slopes of the three tasks.

Recall that we suggested three possible models: Enumeration before, during, and after item definition. From this study, it is easy to eliminate the before-definition model. All the RTs are much lower than would be expected if subjects had to count to 24 first, which should require about 6s, extrapolating from the results of Trick, Enns, and Brodeur (1996). Moreover, RT increased, rather than decreased, with increasing numbers of distractors.

The enumeration-during and enumeration-after models differed only in their predictions about the size of the correlation between search slopes and number discrimination slopes. The during model assumed that correlations across condition would approach 1.0, while the after model assumed they would approach zero. In fact, the correlations between number discrimination slopes in the 1–3 range and search RT slopes were significant, $p < .05$: $r(16) = +0.57$ for standard search, and $r(16) = +0.68$ for multiple target gain, which permits the after model to be dismissed in the general case. However, both models assumed that the slope would be either constant throughout the number range or diminishing, and that was not true in any of the conditions where there was no evidence of speed–accuracy trade-offs.

An alternative to these models is the FINST account of enumeration (Trick & Pylyshyn, 1993, 1994), a more complex model that suggests that there are different types of enumeration processes depending on the number of items in the display, and on the attentional requirements of the item definition processes. Subitizing behaves like a limited version of the enumeration-after-definition model, one that works only for small numbers of items and only when targets pop out of distractors in search. The enumeration slope in the subitizing range comes from processes after definition of the item as a target: Specifically, individuating the item and augmenting the memory counter. Counting involves enumeration-during-definition, which requires moving the attentional focus and marking the already attended items. Subjects would only count in the 1–3 range if they had to use attention to determine which items were targets and which were distractors (indicated by high slopes in the search tasks). If this were true, part of the enumeration slope would be determined by the search slope (the time to find each item) and part would be determined by the counting operations.

Thus, when there is a mixture of stimuli, as there was in this experiment, the size of the correlation between search slope and the number discrimination slope in the 1–3 range would depend on the particular stimuli included. In this study, about half of the conditions were expected to require attentional search. There was a correlation between the search slopes and number discrimination, but it wasn't perfect, and it is therefore important to examine conditions that produced discrepant results. These may be informative about processes peculiar to enumeration (especially individuation and marking).

First, there were conditions where number discrimination slopes were lower than expected, given the search slopes. In these cases, the search slopes were relatively high even when compared with other stimuli (e.g. hard length × orientation in Condition 9, and to a lesser extent, the Triple conjunction of hard length × orientation × brightness in Condition 10). At least in the 1–3 range, this pattern would fit the enumeration- after-definition model. For these stimuli, defining the target was a time-consuming process. Building a representation that distinguished between targets consumed time that was dependent on the display size, but once the target was defined the processes of individuation and marking could carry on as rapidly as if the targets and distractors differed by only a single feature.

Second, there were cases where number discrimination slopes were higher than expected. In general, all of the targets defined by spatial relations between parts had higher 1–3 range slopes than would be expected on the basis of their search slopes. Some of these number discrimination slopes even exceeded 400+ items. Such a result might be expected if the computation of spatial relations itself requires individuation and marking. This fits the enumeration-during-definition model, but in this case enumeration and target definition compete for the same resources and thus interfere with one another. Interestingly, there were conditions in this group with essentially identical search measures, but very discrepant number discrimination slopes. For example, Lighting (Condition 11) and Orientation + Lighting (Condition 12) yielded standard search slopes of 10–12ms/item, multiple target slopes of 13–14ms/item (Table 7), but 1–3 range number discrimination slopes of 187ms/item for Condition 11 and 652ms/item for Condition 12. Targets defined only be direction of lighting, therefore, were much easier to enumerate than those that differed in both direction of lighting and 3D orientation. Obviously, additional stimulus information does not necessarily facilitate enumeration.

Finally, there was the very strange case of the shape-from-shading stimuli in Condition 18. Both the standard search slope and multiple target gain were high, suggesting that attentive search was required. This would ordinarily be associated with a large enumeration slope. In this case the 1–3 range slope was negative (–214ms/item), but reversed direction in the 7–9 range (+314ms/item). A negative slope might be explained by some globally co-operative algorithm, in which additional targets help to facilitate the detection of other targets. However, if this were the case, why wasn't the multiple target gain also larger? In fact, the gain for this condition was not outstanding, certainly not different than the other conditions that required attentional processing in search. Either these similar gains belied very different processes in detection, or there is something uniquely difficult about individuating and marking top-lit spheres amidst bottom-lit distractors that is alleviated by a small increase in the number of targets. To complicate things further, there were individual differences between subjects. Some yielded a large negative slope in the 1–3 range while others produced a small positive slope. These differences may be attributable to strategies, although it is difficult to understand why the same subjects with large negative slopes in Condition 18 showed only a moderately large positive slope in the 1–3 range in Condition 17.

Implications for FINST Theory

FINST theory predicts that for stimuli which permit "pop-out" search, the enumeration slope for a small number of items will also be small, since these items can be tagged preattentively by a limited-capacity spatially parallel mechanism. For stimuli which do not pop out, the slope should be similar for small and large numbers. In fact, this interaction of condition and number range was observed, even after the conditions where 7–9 range accuracy fell below 85% were removed, $F(13, 196) = 11.5$, $p < .01$, MSE = 122,113; and $F(17, 248) = 10.6$, $p < .01$, MSE = 129,090, if these conditions were included. In some conditions, the 1–3 range slopes were significantly lower than those for the 7–9 range. In others, the difference was not significant.

Overall, the 7–9 range slopes were not as strongly related to search slopes as were the 1–3 range slopes. The 7–9 range slopes were 284, 193, 261, 294, 270, 326, 269, 289, 250, 279, 387, 51, –435, 144, 105, –341, 265, and 314ms/item for conditions 1–18 respectively. That is, for the most part, slopes fell between 250 and 350ms/item, for the experiments where the 7–9 range accuracy level was respectable overall (more than 85%). For these stimuli, slopes were not as strongly correlated to the search slope, $r(10) = +0.22$, or to gain, $r(10) = +0.19$, $p > .05$. This is expected if the slope for large numbers of items is determined by several factors other than attentional scanning (see Trick & Pylyshyn, 1994). For example, most adults try to count by groups in the counting range and this can be made more or less difficult by the particular configuration of the items in the display.

Although these findings are generally consistent with FINST theory, the predicted associations between low slopes in search and the 1–3 range in enumeration were only observed for easily discriminable features and conjunctions. For some of the more complex stimuli there were discrepancies, suggesting that the two tasks were tapping different aspects of preattentive processing. For example, enumeration may not always be able to exploit the information that permits pop out in search, perhaps because the same processing resources are required for both preattentive pop-out and subitizing. Conversely, search tasks may not always be able to exploit the information that permits subitizing, perhaps because the necessary information arrives too slowly to benefit search. In short, for purposes of FINST theory, results from a pop-out task may not be sufficient to predict which targets and distractors will permit the selective indexing of a small number of items.

Conclusion

These data have opened up several interesting issues. Neither present theories of enumeration, nor present theories of vision are capable of accounting for the full range of results. None the less, it is apparent that the distinction between preattentive and attentive processes is important in enumeration. Enumeration, even of one to three items, does not always involve the same operations. Instead, the attentional requirements of the particular stimuli to be enumerated seems to dictate whether subitizing occurs or not. Theories of enumeration must take this into account if they are to explain the wide range of things we can enumerate.

This research also contributes to the research on attention. First, the present study shows that standard visual search and multiple target search produce consistent results overall. Thus, any discrepancies between standard search and texture segmentation tasks are not simply due to the greater spatial density or number of targets in texture segmentation. Search and texture segmentation tasks differ in many other ways, as discussed earlier in this paper. Perhaps these tasks tap different preattentive processes. Second, by comparing the enumeration and search tasks directly, it has been possible to learn that pairs of stimuli that are treated the same for purposes of search are not necessarily treated the same for purposes of enumeration. This suggests that there may be several different types of process that can yield small slopes in search, some of which interfere with enumeration and some of which do not. Findings such as these should increase our general understanding of vision, one that goes beyond the simple detection of an item to encompass the mental representation of the entire visual display.

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