Attention in visual search: Multiple search classes

MARYLOU CHEAL and DON R. LYON

University of Dayton Research Institute, Higley, Arizona

Data from visual-search tasks are typically interpreted to mean that searching for targets defined by feature differences does not require attention and thus can be performed in parallel, whereas searching for other targets requires serial allocation of attention. The question addressed here was whether a parallel-serial dichotomy would be obtained if data were collected using a variety of targets representing each of several kinds of defining features. Data analyses included several computations in addition to search rate: (1) target-absent to target-present slope ratios; (2) two separate data transformations to control for errors; (3) minimum reaction time; and (4) slopes of standard deviation as a function of set size. Some targets showed strongly parallel or strongly serial search, but there was evidence for several intermediate search classes. Sometimes, for a given target-distractor pair, the results depended strongly on which character was the target and which was the distractor. Implications from theories of visual search are discussed.

When observers are asked to search for a target in a visual display, the data frequently have been interpreted in terms of attention processes (such as parallel vs. serial allocation of attention). However, most of the inferences about the use of attention are based on the rate of increase in search time with an increase in the number of characters in the display. It is possible that consideration of other measures of performance in addition to search rate would lead to a clearer picture of the role of attention in visual search.

The purpose of the present research was to analyze visual-search performance using a number of empirical measures. These measures included (1) increase in search time with the number of nontarget characters (distractors), (2) the number of errors, (3) the minimum reaction time (RT) to find a target for any one condition, and (4) measures of variability. In the present research, a wide variety of targets was used. Our hypothesis was that these targets might cluster according to their scores on various measures. If several different measures test the same thing, then they should correlate strongly across target types. On the other hand, if the measures do not correlate, it might indicate that they are testing different aspects of search. It was found that the data from multiple targets clustered into five classes of search. The various indicators of search type were then used to propose search strategies for each class.

To provide a useful analysis with the multiple measures, we will first briefly review some critical issues in visual search that have been discussed in the literature and some of the current theories of visual search. Critical issues include parallel versus serial search, exhaustive versus self-terminating search, limited versus unlimited capacity, difficulty of the discrimination, the possibility of mixed search strategies, and alternative dependent measures. Theories that are examined briefly are feature integration theory, both the early (Treisman, 1986; Treisman & Gelade, 1980) and more recent versions (Treisman, 1991; Treisman & Gormican, 1988); guided search (Cave & Wolfe, 1990; Wolfe, Cave, & Franzel, 1989); and similarity theory (Duncan & Humphreys, 1989).

Critical Issues in Visual Search

Parallel versus serial search. Several analyses of visual search have suggested that some stimulus arrays can be searched in parallel, whereas others require that an attentional "spotlight" be directed serially to different display locations until the target is found (e.g., Hoffman, 1979; Treisman, 1986; Treisman & Gelade, 1980). Fast searches that are not affected by the number of distractors are thought to occur in parallel, but searches that are slowed considerably by increasing numbers of distractors are thought to be conducted serially. Typically, the slope of RT as a function of the number of distractors is used as the dependent measure to determine parallel versus serial search (although there are some exceptions; Egeth & Dagenbach, 1991; Townsend, 1990). If the function is flat, the search is considered to be done in parallel, that is, processing of all characters begins simultaneously and proceeds until processing of all characters is completed unless terminated for some reason (such as finding the target). If RT increases with increasing number of distractors and the slope of the RT function is twice as steep

This research was funded by the Air Force Office of Scientific Research (Life Sciences Task 2313T3) and the Air Force Human Resources Laboratory (Contracts F-33615-87-C-0012 and F-33615-90-C-0005). The authors thank J. Wolfe for comments on an earlier unpublished manuscript that included these data, A. Treisman for helpful suggestions, and S. Shoemaker and C. Voltz for programming assistance. Correspondence should be addressed to MaryLou Cheal, University of Dayton Research Institute, P.O. Box 2020, Higley, AZ 85236-2020 (e-mail: cheal%hrloftl.decnat@hqhsd.brooks.af.mil).

STIMULI CHOSEN TO REPRESENT PARTICULAR FEATURES												
COLOR			LINE ORIENTATION				CURVATURE	LINE ENDINGS			NO SINGLE FEATURE	
RG	RY	GY	LI	SL	Ys	OY	CU	Es	Ms	Ws	Ts	OT

Red —												
Yellow												
Green ----												

Figure 1. Pairs of stimulus types arranged by feature that might have facilitated search. Both characters in each pair were the target on an equal number of trials, randomized within blocks. Colors (red/green [RG], red/yellow [RY], green/yellow [GY]) differed in hue and in luminance (see Table 1), horizontal and vertical lines (LIs) and slanted lines (SLs) differed in line orientation, Ys and oblique Ys (OYs) differed in both line orientation and line arrangement, curve versus angle (CU) differed in curvature, E versus S (Es) and M versus S (Ms) differed in number of line endings, M versus W (Ws) had the same number of line endings and only differed in line arrangement, and sideways Ts and oblique Ts (OTs) differed in line arrangement, which is not a unique feature. Note that the two characters in each pair were composed of the same number of pixels so that luminance differences only occurred with colors.

for trials without a target as for trials with a target, search is thought to be conducted serially. In this case, characters are processed in turn, with each additional character only processed after completion of the prior character (Townsend, 1971).

Exhaustive versus self-terminating search. Increasingly, there are instances when data do not easily fit a parallel-serial dichotomy and such a dichotomy may be an oversimplification (Cavanagh, Arguin, and Treisman, 1990). A complicating factor might be whether the search is self-terminating or exhaustive. In self-terminating searches, processing ends when the target is found, whereas in exhaustive searches, all characters are searched before processing ends. Both parallel and serial searches can be either self-terminating or exhaustive.

Capacity. Another issue related to search is the capacity it requires. The number of distractors in the display can be varied in order to test capacity (Townsend & Ashby, 1983). If the task is more difficult with more distractors (longer RTs or poorer accuracy), then capacity is said to be limited. If not, it is said to be unlimited. Supercapacity is indicated by an *improvement* in performance with increasing set size (Townsend & Ashby, 1983). This improvement may occur because the adjacency of the target and distractors resulted in comparison coding rather than coding of individual characters (Treisman & Gormican, 1988).

Difficulty of the discrimination. Search rate may also be related to the difficulty of the discrimination between target and distractors (target-distractor similarity; Duncan & Humphreys, 1989). Although target-distractor similarity may account for some anomalous increases in RT

with increasing numbers of distractors, Treisman (1991) has found evidence that similarity alone is insufficient to account for other anomalous results in search tasks. The implications of variation in discrimination difficulty will be elaborated further in the Discussion.

Mixed search strategies. Another possibility is that for some targets, more than one search strategy is used. One possible support for this hypothesis would be a bimodal distribution of RTs: short RTs when parallel search is used, and longer RTs when serial search is used. This distribution could occur if the strategy changed between trials. Although the occurrence of this distribution of RTs would support mixed strategies, absence of such a distribution would not negate the hypothesis, because strategies could be mixed within a trial (Townsend, 1971).

Additional measures for identification of search strategies. Further questions concerning search strategy were suggested a number of years ago by Townsend (Townsend, 1971; Townsend & Ashby, 1983). He proposed that the slope of the RT function is not, by itself, adequate to explain the processes that occur during visual search. One problem with the use of slope to compare these different targets is that increases in RT with set size

Table 1
Color Stimuli

Color	u'	v'	Luminance (cd/m ²)
White	.1792	.4462	140.9
Red	.3668	.5128	42.3
Yellow	.1811	.5506	171.7
Green	.1324	.5568	176.8

Figure 2. Method for visual-search task depicting search for a horizontal line in vertical distractors. Following a fixation bar, one screen with either 2, 9, or 24 characters was presented until the observer responded as to whether a target was present or not. If a target was present (a character that differed from the rest), it appeared in a random position, as did all of the distractors. Note that relative sizes of characters and spaces are not accurate. See text for accurate description.

can be based on two factors: the fact that more items are processed when more are present, and possible increases in the time to process each item (Cave & Wolfe, 1990). Thus, although slope and slope ratios are useful measures, their analysis alone may not give a good indication of the type of search used for all target types.

Townsend and Ashby (1983) proposed several other measures that can be considered. For instance, they considered the relationship between errors and RT. They suggested that a self-terminating search requires less expenditure of energy than does an exhaustive search and results in shorter RTs, but any error due to stopping too soon on target-present trials might result in shorter RTs than would be the case if the search were continued until the target was found. To account for this possibility by including error information, Townsend and Ashby used a ratio of RT to accuracy (or proportion correct) for each experimental condition.

Figure 3. Reaction times (RTs, in milliseconds) as a function of set size for Experiment 1. Upper graphs (A, D, G) depict RT as a function of set size (squares, left scale) and proportion of errors (triangles, right scale) for target-absent (—, filled symbols) and target-present (+, open symbols). Center graphs (B, E, H) show data after Correction 1, made by dividing RT by proportion correct for each set size. Bottom graphs (C, F, I) show data after Correction 2, made by dividing RT by proportion correct for target-present trials for each set size. Left graphs (A, B, C) are data for slanted lines. Center graphs (D, E, F) are data for sideways Ts. Right graphs (G, H, I) are data for Ys.

Table 2
Analysis of Variance for Experiment 1

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Target type	2,14	40.37‡	42.86‡	40.75‡
	Set size	2,14	61.71‡	29.44‡	54.15‡
	Presence	1,7	30.42‡	21.47*	30.92*
	T×S	4,28	55.94‡	45.67‡	49.02‡
	T×P	2,14	9.90*	5.66	10.14‡
	S×P	2,14	21.14‡	2.63	22.03‡
	T×S×P	4,28	10.91‡	1.66	12.05‡
SLs	Set size	2,14	0.30	0.89	0.06
	Presence	1,7	11.80	9.82	11.95
	S×P	2,14	1.31	0.49	1.40
Ts	Set size	2,14	81.05‡	52.06‡	70.33‡
	Presence	1,7	19.56*	10.63	19.50*
	S×P	2,14	26.06‡	4.31	24.04‡
Ys	Set size	2,14	9.08*	3.54	6.54*
	Presence	1,7	41.33‡	54.55‡	42.35‡
	S×P	2,14	3.59	0.60	3.94

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions.

* $p < .01$. † $p < .001$. ‡ $p < .0001$.

Errors can also be considered in another light. As suggested by A. Treisman (personal communication, 1991), it is quite probable that some errors are due to an early interruption of the search. If search is interrupted before the target is detected on target-present trials, an error results and RT is presumably shorter than it would have been had the trial not been interrupted. Dividing RT by proportion correct on target-present trials, as Townsend and Ashby (1983) suggested, will lengthen RTs to correct for this effect. On the other hand, until a target is found, target-present trials look just like target-absent trials. Thus, on target-absent trials, if the observer stops too soon, the trial is correct. Yet, RT for such trials is also underestimated. Instead of correcting RTs on these trials using target-absent errors, which are not necessarily related to stopping too soon, a more useful correction might be to divide both target-present and target-absent RTs by proportion correct on *target-present* trials. Both corrections will be considered below.

Other suggestions made by Townsend and Ashby (1983) may also be useful. Although their ideas have not been rejected, they have been mainly ignored. In the present paper, data collected with a variety of targets in a search task were analyzed by several methods. The following assumptions, discussed by Townsend and Ashby, were used to separate the targets into various classes.

1. If RT does not increase with set size, the search is assumed to require little or no processing capacity, whereas if RT increases with set size, the search is assumed to require processing capacity.

2. If the target-absent slope is at least twice as steep as the target-present slope, search is considered to be self-terminating. If the search is self-terminating, then the target should be found, on average, when half of the items in the display have been examined. On the other hand,

if there is no target, search will continue until all characters have been examined (exhaustive search).

3. A 2:1 target-absent to target-present slope ratio can be expected to result in an interaction between set size and target presence.

4. It is assumed that search is exhaustive on most target-absent trials; that is, all characters are examined before a decision as to presence of the target is made. If the slope for target-present trials is as steep as the slope for target-absent trials, search on target-present trials is then considered to be exhaustive. This may indicate that each item was searched before deciding whether or not there was a target, even when a target was present.

5. In a serial search, it is assumed that the target is processed first on some proportion of the trials. As the number of characters increases, the proportion of trials in which the target is the first one processed decreases. Thus, there is a smaller sample of target first-trials for large set sizes. Furthermore, the probability of obtaining an extreme minimum RT is low when the sample size is small. Therefore, if there is the same number of trials for each set size, minimum RT should increase with set size (see Townsend & Ashby, 1983, pp. 128-130). Also, in limited-capacity, self-terminating searches, minimum RT can increase with set size because it may take longer to process each character when more are present. Minimum RT can also increase with set size for unlimited-capacity, self-terminating searches.

6. There should be more increase in variability with increased set size in the target-present condition than in the target-absent condition in a serial search, because of the greater number of possibilities for finding the target and terminating the search (Townsend & Ashby, 1983, pp. 203-205). Of course, variability will also vary as a function of the item being searched (A. Treisman, personal com-

Table 3
Analysis of Variance for Errors

Experiment	Effect	df	F	Experiment	Effect	df	F
1	Target type	2,14	5.83	2	Target type	2,14	4.60
	Set size	2,14	1.75		Set size	2,14	3.44
	Presence	1,7	0.46		Presence	1,7	10.68
	T×S	4,28	1.79		T×S	4,28	4.61*
	S×P	2,14	30.41‡		S×P	2,14	10.53*
	T×S×P	4,28	7.04†		T×S×P	4,28	8.38‡
3A	Target type	1,8	4.60	3B	Target type	1,7	9.87
	Character	1,8	18.02*		Character	1,7	12.79*
	Set size	2,16	32.81‡		Set size	2,14	7.03*
	Presence	1,8	56.73‡		Presence	1,7	28.95†
	T×C	1,8	11.20*		T×C	1,7	15.93*
	T×S	2,16	1.72		T×S	2,14	6.30
	T×P	1,8	0.29		T×P	2,14	23.99*
	C×S	2,16	15.32†		C×S	2,14	12.21†
	C×P	1,8	12.29‡		C×P	1,7	13.41*
	S×P	2,16	58.45‡		S×P	2,14	18.21‡
	C×S×P	2,16	20.25‡		C×S×P	2,14	10.36*
	T×C×S×P	2,16	2.35		T×C×S×P	2,14	6.37
4: Curve	Character	1,8	13.13*	4: Color	Target type	2,14	1.18
	Set size	2,16	7.30*		Set size	2,14	2.12
	Presence	1,8	22.76*		Presence	1,7	1.56
	C×S	2,16	16.03†		T×S	4,28	1.80
	C×P	2,16	9.13		T×P	2,14	0.41
	S×P	2,16	25.00‡		S×P	2,14	13.61†

Note—Interactions that are not listed did not reach .01 statistical significance. * $p < .01$; † $p < .001$; ‡ $p < .0001$.

munication, July 18, 1991). This variance may increase with an increase in set size, but there is no apparent reason to expect it to differ as a function of whether or not the target is present. Interpretation of this variability measure may be subject to question for another reason. There have been inconsistencies in recent publications as to whether or not variability increases more with set size for target-present trials than for target-absent trials (Treisman, 1991; Ward & McClelland, 1989).

An example of how these criteria will be used is the case of a limited-capacity, exhaustive serial search. For this kind of search, one would expect an increase in RT with set size, approximately equal target-present and target-absent slopes, no set size $\times$ target presence interaction, an increase in minimum RT with set size, and more increase in variability with set size for target-present than for target-absent trials. The main measures that separate this search strategy from limited-capacity, self-terminating serial search are a relatively high slope ratio and a large set size $\times$ target presence interaction.

Theories of Visual Search

Different theories have attempted to account for the different issues related to visual search. This paper presents new data that need to be accounted for by a good theory of visual search. Therefore, a brief description of some of the theories follows. Those to be considered include different versions of feature integration theory (FIT), guided search, and similarity theory.

Glossary. Before presenting brief descriptions of the theories, a short glossary may be useful. A number of terms will be used here as they are currently used in the

visual-search literature. For instance, in a display containing several characters, the character being sought is a *target*; the other characters are *distractors*. *Set size* refers to the number of characters in a single display. A *feature* is an easily distinguishable stimulus dimension such as color or line orientation. Targets that differ from distractors in the value of only one feature are referred to as *feature targets*, and search for such a target is called a *feature search*. Targets that differ in more than one feature, as is usually the case in searching for a particular letter among other letters, are called *nonfeature targets*. If a target is defined by two or more features (e.g., a green vertical line in red vertical and green horizontal distractors), it is called a *conjunction target*. An *asymmetry* refers to a case in which reversing the background character and the target character greatly changes the search rate.

Feature integration theory. The visual-search task evolved from earlier ideas of two stages of visual processing, an early parallel process and a later serial process (Neisser, 1967). The study of visual search has led to the feature integration theory (FIT) of attention (Treisman, 1986; Treisman & Gelade, 1980).

According to this theory, visual perception has two stages: a fast, "preattentive" stage of processing, where search is in parallel and basic features are identified, and a slower, serial stage of processing, where search requires a concentration of attention to combine the features into complex characters. A distinction is often made between the search for feature and nonfeature targets. When targets differ from distractors by a single feature, a search can be made in parallel across all characters and there is no need for attention. In contrast, when targets must

Table 4
Slopes of Reaction Time by Set Size

Targets	Target-Present Slopes		Target-Absent Slopes			Absent/Present Slope Ratios		
	Not Corrected	Correction 1-2	Not Corrected	Correction 1	Correction 2	Not Corrected	Correction 1	Correction 2
Slants	-0.4	-0.6 (2)	1.1	0.2	1.0	-2.8 (2)	-0.4 (3)	-1.7 (1)
Ts	11.8	18.7 (14)	26.1	23.2	36.2	2.2 (11)	1.2 (9.5)	1.9 (10)
Ys	1.5	2.5 (5)	5.5	3.8	7.2	3.7 (16)	1.5 (11)	2.9 (14.5)
Lines	-1.0	-2.0 (1)	1.3	1.1	0.3	-1.3 (4)	-0.5 (2)	-1.5 (2)
Oblique Ts	10.0	16.2 (13)	21.0	18.8	29.1	2.1 (10)	1.2 (9.5)	1.8 (9)
Oblique Ys	5.5	8.7 (10)	15.4	13.8	20.4	2.8 (13)	1.6 (12)	2.3 (11.5)
M in Ss (A)	22.5	48.8 (18)	23.6	19.6	53.0	1.0 (6.5)	0.4 (5.5)	1.1 (6.5)
S in Ms (A)	9.6	9.2 (12)	40.9	39.8	41.6	4.3 (17.5)	4.3 (18)	4.5 (18)
E in Ss	21.7	44.1 (17)	21.4	20.1	43.9	1.0 (6.5)	0.5 (7)	1.0 (4.5)
S in Es	14.3	18.8 (15)	34.9	35.1	42.7	2.4 (12)	1.9 (14)	2.3 (11.5)
M in Ss (B)	18.8	49.1 (19)	18.3	16.7	48.3	1.0 (6.5)	0.3 (4)	1.0 (4.5)
S in Ms (B)	6.6	9.1 (11)	30.3	28.9	34.5	4.6 (19)	3.2 (17)	3.8 (16.5)
W in Ms	3.3	4.0 (7)	14.3	12.4	15.3	4.3 (17.5)	3.1 (16)	3.8 (16.5)
M in Ws	4.6	8.2 (9)	14.8	13.7	20.1	3.2 (14)	1.7 (13)	2.5 (13)
Angle in curve	2.7	3.5 (6)	9.0	7.2	10.1	3.3 (15)	2.1 (15)	2.9 (14.5)
Curve in angle	8.7	21.7 (16)	16.4	17.7	33.5	1.9 (9)	0.8 (8)	1.5 (8)
Red/Green	0.2	-0.1 (3)	-0.9	-1.3	-1.3	-4.5 (1)	21.7 (19)	13.0 (19)
Red/Yellow	0.7	1.4 (4)	-1.5	-2.9	-1.0	-2.1 (3)	-2.1 (1)	-0.7 (3)
Green/Yellow	3.4	4.8 (8)	3.5	1.9	5.1	1.0 (6.5)	0.4 (5.5)	1.1 (6.5)

Note—Numbers in parentheses are rank order for that measure. Slopes are the mean of individual slopes based on median reaction time (RT) for columns 2, 4, and 7 and the mean of individual slopes based on corrected data for other columns. Correction 1-2: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions; used for both Correction 1 and Correction 2. Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for target-present trials in both target-absent and target-present conditions.

be identified by a conjunction of features or there is no unique feature difference, the search requires serial processing, which involves focused attention on each character in turn.

Although visual search has provided much useful information, there are problems. One problem with this theory is that it has been difficult to arrive at an independent definition of a feature (Bravo & Blake, 1990; Briand & Klein, 1989). Sometimes, features are just those qualities in a character that allow parallel search. The early suggestion that features might be those targets for which there were distinct channels in the central nervous system (Julesz, 1982) may not account for some parallel searches, such as particular conjunctions of two or more features (Treisman & Sato, 1990). If parallel processing is mediated by single units, then there would need to be specialized units for conjunctions that are found with parallel search (such as color and form, color and motion, or color and binocular disparity; Green, 1991). However, Treisman and Sato found that no single feature determined the ease of search for conjunctions. Instead, they found that (1) correspondence between search slopes and physiological evidence was weak, (2) rejection of two known distractor conjunctions could not be done in parallel even though it was possible to reject four known features, and (3) it was possible to predict search rates for known conjunctions by assuming additive contributions from each component feature. None of these problems are definitive, and they do not rule out certain single-fiber activations, which may be responsible for perception of a particular feature (e.g., motion; Newsome, Britten, & Movshon,

1989; Salzman, Britten, & Newsome, 1990). However, taken together, the data suggest that the physiological system is more complex than a single line/single feature conception.

The study of conjunction targets presents another problem for the idea that only feature targets can be searched in parallel. Search for conjunctions can be made without focused attention (i.e., there is little or no increase in reaction time with increasing number of distractors) in particular circumstances (Wolfe et al., 1989). The combination of spatial frequency and orientation (Sagi, 1988) or of stereoscopic disparity (stimuli on different planes) and either color or motion can be searched in parallel (Nakayama & Silverman, 1986). Also, a three-way conjunction (color, shape, and size, or color, orientation, and size) may be detected more easily than a two-way conjunction (Quinlan & Humphreys, 1987; Wolfe et al., 1989). Furthermore, some of the functions of RT $\times$ number of distractors for features show increases in RT with increasing number of distractors (Treisman & Gormican, 1988). Thus, the possibility exists that there are cases where search is neither strictly parallel nor completely serial.

Newer feature integration theory. The original FIT, with its emphasis on a dichotomy between feature and nonfeature (or conjunction) targets, does not appear to accommodate data for which the scores do not fit readily into such a dichotomy. Fortunately, FIT has proved to be dynamic, with many changes as new data appear. In more recent versions of the theory, other mechanisms are posited to explain data that do not appear to be the result

Table 5
Dependent Measures by Target Type

Targets	Search Rate Med RT	Search Rate Correction 1	Search Rate Correction 2	Increase in Minimum RT with Set size*	Slope for SD + †	Slope for SD - ‡
Slants	0.4 (4)	-0.2 (4)	0.2 (3.5)	-21 (1)	-0.07	-0.74
Ts	19.0 (15)	20.9 (14)	27.5 (14)	94 (16)	9.77	9.91
Ys	3.5 (5.5)	3.2 (5)	4.9 (5)	32 (8)	-0.01	2.93
Lines	-0.2 (3)	-0.5 (3)	-0.9 (1)	-10 (2)	-0.85	1.31
Oblique Ts	15.5 (12)	17.5 (11)	22.7 (12)	79 (12)	11.19	8.22
Oblique Ys	10.5 (10)	11.2 (10)	14.6 (10)	27 (7)	4.52	5.89
M in Ss (A)	23.1 (17)	34.2 (19)	50.9 (19)	113 (18)	13.66	4.61
S in Ms (A)	25.3 (19)	24.5 (15)	25.4 (13)	91 (15)	8.17	11.85
E in Ss	21.6 (16)	32.1 (17)	44.0 (17)	120 (19)	8.05	6.05
S in Es	24.6 (18)	27.0 (16)	30.8 (16)	66 (11)	8.42	7.48
M in Ss (B)	18.6 (14)	32.9 (18)	48.7 (18)	84 (13)	9.69	3.78
S in Ms (B)	18.5 (13)	19.0 (12)	21.8 (11)	64 (10)	8.05	9.18
W in Ms	8.8 (8)	8.2 (8)	9.7 (8)	44 (9)	2.82	6.57
M in Ws	9.7 (9)	11.0 (9)	14.2 (9)	89 (14)	2.54	5.68
Angle in curve	5.9 (7)	5.3 (7)	6.8 (7)	21 (4)	3.35	7.33
Curve in angle	12.6 (11)	19.7 (13)	27.6 (15)	98 (17)	0.08	9.04
Red/Green	-0.4 (1.5)	-0.7 (2)	-0.7 (2)	-6 (3)	0.19	-0.75
Red/Yellow	-0.4 (1.5)	-0.8 (1)	0.2 (3.5)	26 (6)	-0.20	-0.36
Green/Yellow	3.5 (5.5)	3.4 (6)	5.0 (6)	22 (5)	5.15	0.90

Note—Numbers in parentheses are rank order for that measure. Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for target-present trials in both target-absent and target-present conditions. *For target-present trials; negative numbers indicate a decrease. †Slope of standard deviation for target-present trials. ‡Slope of standard deviation for target-absent trials.

of either parallel or serial processing (Treisman & Gormican, 1988). For instance, in cases where there is a fairly large difference in responses as a function of which character of a pair of characters is the target and which is used for the distractors, they suggested that the presence of a feature is found efficiently. In contrast, the absence of a feature is not found rapidly. In cases where the quantity of a feature (such as the amount that a slanted line differs from vertical) varies, the character with more of the feature (i.e., further from the reference value) will be found more readily than will the character with less of the feature. In this type of task, search may be serial in both cases but there is a shallower slope for the target with more of the feature. Thus, more attention may be needed to find the feature that is closer to the reference value.

Additionally, Treisman (1991) argues that search is more difficult for a target that has a *standard feature*, that is, a straight line among curved lines, a vertical character among tilted characters, parallel lines among converging lines, or a closed circle among circles with gaps. A nonstandard target is proposed to contain an element in addition to a standard feature (i.e., straight line plus curvature, vertical plus some tilt, parallel plus convergence, or circle plus a gap).

Another suggestion by Treisman and Gormican (1988) is the possibility for rapid searches when there is no apparent feature. In some cases, some of the distractors may group, or cluster, together, so that search is parallel within groups but is serial between groups.

Guided search model. The guided search model has been proposed to address some of the problems with FIT (Cave & Wolfe, 1990; Wolfe et al., 1989). This model combines the feature integration aspect of FIT (Treisman

& Gelade, 1980) with concepts from Hoffman's (1979) two-stage model. In FIT, an early, parallel stage of search and a later, serial stage were held to be independent. Hoffman's model proposes that the first stage guides the second stage, rather than being independent of the second stage as in FIT. Guided search expands on this idea as follows: (1) the parallel stage produces an activation map for each feature type that guides the second, slower stage to possible targets, (2) the activity in all feature maps is summed into an activation map, and (3) feature integration and perception of the target occur only in the second, serial stage.

The guided search model seems to handle many data that were a problem for FIT. There is no need to assume a dichotomy between feature search and conjunction search for two reasons: the parallel stage in this model can guide the serial stage, and there is proposed noise in the system. Noise, which refers to unknown variables that interfere with target detection or discrimination, may slow a feature search. Also, the serial stage may find a target more quickly because it is guided by the parallel stage. This guidance may result in fewer items being searched, or it may mean less time examining each item.

Similarity theory. In similarity theory (Duncan & Humphreys, 1989), a clear separation of parallel and serial search is not necessary. Instead, there can be a continuum of search efficiency. Searches become more difficult as the target and distractors become more similar and the distractors become less similar to each other. In the present paper, distractor-distractor similarity will not be discussed because all distractors are identical in the present experiments. This theory has three components: (1) a parallel stage of perceptual description, (2) a selective process based on matching descriptions from the parallel pro-

Figure 4. Reaction times (in milliseconds) as a function of set size for Experiment 2. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for LIs. Center graphs (D, E, F) are data for OTs. Right graphs (G, H, I) are data for OYs.

cess to relevant information stored previously, and (3) entry of that selected material to limited-capacity, visual short-term memory (VSTM).

In the parallel stage, parts of a larger whole (such as letters of a word or fingers of a hand) must be grouped together, forming *structural units*. These units prepare the observer for appropriate relationships between stimuli during the selection phase. Such a grouping may be by spatial proximity, by similarity (both visual similarity and characteristics retrieved from memory), by concurrent motion, and by other shared properties. This first stage has no immediate control over behavior.

The second, selective process must be flexible enough to handle all situations but still needs to be directed according to the particular search in progress. One important result at this level is the rejection of nontargets in groups (where linked) rather than individually. Thus, there are two factors in selection. One is the match of any item with the currently needed item. The other is related to grouping; those items that group together either match or are rejected as a group.

Duncan and Humphreys (1989) suggest that VSTM has both parallel and serial components. It is parallel for any one input into VSTM, but because VSTM fills rapidly,

it must be emptied for another input. Therefore, it is serial from one period of input to another.

Theories of visual search in relation to classifications of search type. These brief descriptions of a few theories of visual search will allow us to consider how each theory would handle the data reported in the following sections. Thus, in addition to empirically determining search classes with multiple methods, we will relate the proposed search classes to the theories.

METHOD

Observers were tested in a visual-search task similar to that used by Treisman (1982). In this task, a display of characters is presented and the observer must respond as quickly as possible as to whether a target is present or not. The set size is varied to provide a measure of the difference in the need for attention as a function of the number of distractor characters. It has been shown that responses to feature targets are rapid, whereas it may take longer to respond to nonfeature targets (Beck, 1966, 1982; Treisman & Gelade, 1980).

Certain differences in procedure were used here to avoid possible confounding of attention with memory. The observer did not have to remember the target in this design because the target was one of two known disparate characters and there were always at least two characters present. In this way, for instance, trials with

Table 6
Analysis of Variance for Experiment 2

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Target type	2,14	60.23‡	61.73‡	61.52‡
	Set size	2,14	35.90‡	34.55‡	37.78‡
	Presence	1,7	32.19‡	15.48*	32.95‡
	T×S	4,28	23.41‡	28.68‡	30.84‡
	T×P	2,14	10.30*	6.01	10.24*
	S×P	2,14	20.09‡	7.01*	18.91‡
	T×S×P	4,28	5.66*	0.50	6.19*
LINES	Set size	2,14	0.07	1.65	1.67
	Presence	1,7	4.90	4.54	4.73
	S×P	2,14	14.14‡	7.21*	14.84‡
OT	Set size	2,14	26.95‡	30.69‡	37.70‡
	Presence	1,7	10.98	5.05	11.23
	S×P	2,14	11.32*	1.71	10.68*
OY	Set size	2,14	46.73‡	39.45‡	32.08‡
	Presence	1,7	33.51‡	19.18*	32.37‡
	S×P	2,14	17.37‡	4.50	17.63‡

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions.

* $p < .01$. † $p < .001$. ‡ $p < .0001$.

a left-facing target could be randomized with trials with a right-facing target without displaying the target between trials. This method avoided possible problems of memory that could account for the longer RT shown with 1 character than with 6 or 12 characters for some stimuli in previous research (Treisman & Gormican, 1988).

In visual search, observers may use a different strategy depending on the set size. In the present task where the target is one of two different characters, when set size is two it is only necessary to decide whether the two characters are the same or different. With larger set sizes, observers may first notice that there are more than one of one character and then search for the other character. (This suggestion was made by an anonymous reviewer.) However, in cases when the target is given prior to each trial, with set size of one the observers must remember the target but with larger set sizes they can either (1) remember the target, (2) decide same/different, or (3) find the multiple distractors before searching for the target. Thus, even in this variation of the task, it is not necessary for the observer to remember the target to determine whether it is present. With the present paradigm, observers may use different strategies for a set size of two than for larger set sizes. On the other hand, if the target is given before the trial, there can also be a difference in strategy for a set size of one and larger set sizes.

It should be stressed that the method used here allowed either one of a pair of characters to be the target on trials within a block. It is possible that some searches would be different if they were blocked by target rather than being mixed within blocks.

Observers

Observers were volunteers from the laboratory. Each stimulus comparison took 10–15 min, and two to four conditions were tested within one experiment. Thus, the total experiment for each observer took from 20–50 min. The observers ranged in age from 24 to 63 years of age and had various visual problems, all of which were corrected adequately to allow focus at the needed distance. It was not possible to test all of the same observers in all experiments because the trials were conducted over a 2-year period. One observer participated in all search experiments, 3 in four experiments, 2 in three experiments, 3 in two experiments, and 11 in only one experiment.

Apparatus

Stimuli were displayed on one of two IBM XTs with enhanced color monitors that had a 60-Hz frame rate. Luminance as measured with a Spot Spectrascan was 99.1 cd/m² for black-and-white experiments. Luminances for colored stimuli are shown in Table 1. Phosphors were P-22-B, P-22-G, and P-22-R, all with decay to 10% in less than 1 msec. With the exception of colored stimuli, the white pixels were presented against a dark-gray background. An extended character set was generated to present the desired characters. An adjustable chin-and-headrest helped to maintain head position at the required distance. Responses were made on a two-button keypad. Eye movements were not monitored, and no instructions were given concerning movement of the eyes.

Stimuli

Thirteen pairs of targets (Figure 1) were tested in four separate experiments, listed in order of completion. The targets were chosen to represent differences in particular features (color, line orientation, curvature, and line endings) plus different configurations of Ts that differed in line arrangement and not by a single feature.

Experiment 1: SLs, Ts, and Ys. The first group of 8 observers was tested with slanted lines (SLs), sideways Ts (Ts), and Ys. SLs were straight lines (as in Figure 1, length = 1° of visual angle) slanted 45° either left or right of vertical; this pair of characters differed from one another only in line orientation. Ts and Ys were oriented to the left or to the right (vertical line = 1.2°; adjoining line = .8°). Ys differed in orientation of the shorter line and in the arrangement of the two lines, whereas Ts did not differ in line orientation but only in the arrangement of the conjoining lines. It was expected that SLs would result in flat slopes and that Ts would result in steep slopes. Ys might result in flat slopes if the difference in line orientation was sufficiently salient. The order for the presentation of the three stimulus types to different observers was counterbalanced.

Experiment 2: LIs, OTs, and OYs. Eight observers were tested with stimuli that were rotated in orientation to those of Experiment 1. These were horizontal (.3°) or vertical (.4°) lines (LIs), left or right oblique Ts (OTs; .9° × .9°), and oblique Ys (OYs) that consisted of an oblique line with the left version having an arm that was horizontal and the right version having an arm that was vertical

Figure 5. Reaction times (in milliseconds) as a function of set size for Experiment 3A. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for M in Ss. Right graphs (D, E, F) are data for S in Ms.

(.9° × .9°). The two characters for LIs, like SLs, differed only in line orientation. OYs differed both in line orientation and in the arrangement of the two lines. OTs, like Ts, did not differ in line orientation but only in line arrangement. The order for the presentation of the three stimulus types to different observers was counter-balanced.

Experiment 3A: Ms and Es. Nine observers were tested with characters that had different numbers of line endings to determine if there would be flat slopes. This might be anticipated if there is no need for attention in the discrimination. Such a possibility would be expected if number of line endings is a feature (Julesz, 1982). One character had three endings, and one had two endings (Ms, see Figure 1; and Es composed of a block backwards E and a block S of the same dimensions as the Ms). These block characters were each constructed to fill a square (.9° × .9°).

Experiment 3B: Ms and Ws. Eight observers were tested with characters of the same dimensions as in Experiment 3A. These characters either had two or three line endings (Ms), or both had three line endings (Ws; Figure 1). It might be expected that Ms might result in flat slopes if number of line endings is a feature, but that Ws would result in steeper slopes. For both tests, order of presentation alternated for successive observers. Only 2 observers participated in both subgroups; thus, there were 7 observers in Group A and six in Group B that were distinct.

Experiment 4: Curve and color. Eight observers were tested on four conditions: curve versus angle (CU) and three color comparisons (red vs. green [RG], red vs. yellow [RY], and green vs.

yellow [GY]). CU allowed testing for curvature in comparison to an angle composed of two straight lines. The angle was used to have characters that were matched in length, width, and number of pixels (luminance). If curvature is a feature, a flat slope would be expected. Flat slopes were predicted for the color comparisons. The curve was the standard left parenthesis, which was a semicircle (.7° × .4° viewed from 38 cm); the angle was created to have the same number of pixels and to be the same height with an angle of approximately 70° (.7° × .3°). All color stimuli were standard plus signs (.6° × .6°). Color discriminations could be based on hue and/or luminance differences (Table 1). Order of presentation was chosen from all possible orders and counterbalanced across observers. An additional observer was tested on only the curve condition.

Procedure

In the present version of a search test, there were three different numbers of set sizes (Figure 2). The screen could contain 2, 9, or 24 characters. On half of the trials, one of the characters was different from the rest (a target-present trial). The stimulus display was arranged with 49 potential locations for characters, but actual locations were separated by at least one row and two spaces, and no character was presented in the fixation position. Within these restrictions, characters were placed in 2, 9, or 24 locations in a random fashion. The target could appear in any of the 25 center positions, and distractors could appear in any of the locations.

Each block of trials was introduced by 12 practice trials. These trials contained one trial of each possible condition, randomized

Figure 6. Reaction times (in milliseconds) as a function of set size for Experiment 3A. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for E in Ss. Right graphs (D, E, F) are data for S in Es.

in a $2 \times 2 \times 3$ design (two target types with the opposite distractors, target-present and target-absent, and set sizes of 2, 9, and 24 characters). Experimental trials for the same stimuli followed immediately (144 trials, 12 each for each of the $2 \times 2 \times 3$ parameters, randomized).

The observers were told that a field of stimuli would appear with 2, 9, or 24 characters. On half of the trials, one of the stimuli would be different from the others. The observers were instructed to press the right key if they saw a disparate character and to press the left key if they did not. They were further instructed to respond as quickly as possible, but to be accurate.

Each observer placed his/her head on a chin-and-headrest (49 cm [Experiment 1] or 38 cm from the screen). A keypress started the session. The first screen contained a fixation point for 500 msec (30 screen refreshes), followed by a display. This display remained on until the response or for 3 sec, whichever came first. The display was then replaced by feedback (either CORRECT or WRONG and the RT) for 1 sec (60 screen refreshes). After an interval of 750 msec, another trial was initiated. Incorrect trials and those with responses delayed longer than 3 sec were retested at the end of the block.

Data analyses. Data were analyzed with an analysis of variance (ANOVA) and regression analyses on median RTs for each observer. Individual median RTs were used (rather than basing the analysis on individual mean RTs) because RT data are not distributed normally. By using medians, the effect of extreme scores is minimized. Additional analyses were computed in two ways with corrections for error (described below). An ANOVA was also computed for error rate. The effect of target character (whether the target was Form A or Form B) is only reported where there was an asym-

metry. Although the error rate was very high in some conditions, these data were retained because the same observers had low error rates in other conditions. Therefore, it was not justified to exclude the data from these observers.

We elected to use a conservative criterion for significance (.01), because with so many different statistical tests we wished to minimize the possibility of considering an effect to be significant when it was not.

Minimum RT for each condition was the mean over all observers of the shortest RT for all trials for the relevant condition of each observer for correct target-present trials. Minimum RTs for correct target-absent trials could likely be due to stopping search too soon and getting the trial correct by default. Therefore, they were not used.

Standard deviations (SDs) were calculated on all of the raw data, with the exception of RTs greater than 3,000 msec. Discarding long RTs resulted in dropping one score from each of 6 of the 114 conditions (19 targets [when a pair of targets resulted in asymmetries, they were treated separately], 3 distractor levels, target-present and target-absent). In comparing the rate of increase in SD for target-present and for target-absent, we arbitrarily required a difference in SD slopes of at least 1 msec to attribute a greater increase in SD for target-present trials.

RESULTS

Experiment 1: SLs, Ts, and Ys (Figure 3)

RTs differed significantly, depending on the target type, the set size, and the presence or absence of the target (Ta-

Table 7
Analysis of Variance for Experiment 3A

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Target type	1,8	4.83	8.11	9.12
	Character	1,8	4.91	3.77	8.62
	Set size	2,16	265.70‡	247.59‡	260.73‡
	Presence	1,8	142.41‡	16.88*	119.27‡
	T×C	1,8	1.13	8.07	12.16*
	T×S	2,16	0.48	1.74	2.38
	C×S	2,16	4.48	6.81*	11.21†
	C×P	1,8	69.65‡	60.92‡	54.25‡
	S×P	2,16	28.08‡	3.34	28.94‡
	T×C×P	1,8	0.20	1.29	0.03
	C×S×P	2,16	47.82‡	52.10‡	33.27‡
	T×C×S×P	2,16	2.87	2.87	1.05
M in Ss (A)	Set size	2,16	118.74‡	198.84‡	94.24‡
	Presence	1,8	9.82	1.46	8.87
	S×P	2,16	1.42	11.95†	1.14
E in Ss	Set size	2,16	36.91‡	40.00‡	41.19‡
	Presence	1,8	6.84	0.88	4.60
	S×P	2,16	1.29	6.58*	0.93
S in Ms (A)	Set size	2,16	101.36‡	81.53‡	53.92‡
	Presence	1,8	210.24‡	99.86‡	298.38‡
	S×P	2,16	126.72‡	58.55‡	145.70‡
S in Es	Set size	2,16	123.30‡	208.28‡	137.70‡
	Presence	1,8	149.17‡	83.19‡	140.95‡
	S×P	2,16	16.96‡	6.72*	20.03‡

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions. Interactions that are not listed did not reach .01 statistical significance. * $p < .01$. † $p < .001$. ‡ $p < .0001$.

ble 2). Median RTs for each observer were analyzed in a comprehensive ANOVA with repeated measures (3 target types [SLs, Ts, Ys], 3 set sizes [2, 9, 24], and presence or absence of the target).

The proportion of errors was not significantly affected by target type (Table 3). There were, however, more errors for Ts and Ys with increases in set size on target-present trials (Figure 3), but not for SLs. These conclusions were supported by the interactions of target type $\times$ set size $\times$ target presence.

On the basis of only the set-size effect, perception of a disparate SL would typically be classified as unlimited-capacity, parallel search, since there was no effect of set size nor any interaction of set size $\times$ target presence (Figure 3A). For Ts, on the other hand, search fit a typical serial pattern, with a large increase in RT with increases in number of distractors and an increase that was twice as great when no target was present (Figure 3D). These data suggest a self-terminating search, because the target-absent slope increased approximately twice as much as did the target-present slope (Table 4, column 7). These data are consistent with data previously collected with similar targets.

It can be noted that in all cases where there were increases in the proportion of errors with set size, the increases were primarily in errors of omission: targets were present but were not reported. Greater errors of omission than of commission have been reported by others as

well (Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Wolfe et al., 1989). Since proportion of errors and RTs are interrelated, errors need to be considered. Correction 1 was a transformation of the data that was suggested by Townsend and Ashby (1983) to adjust for number of errors in each condition. For each observer, the RT for each condition was divided by the proportion correct for the same condition.

Correction 2 for errors was based only on target-present errors. In this case, RTs for both target-present and target-absent trials were divided by the proportion correct for target-present trials for the relevant condition. This would be a more appropriate correction if there were a bias to stop early in both target-present and target-absent conditions. This possibility was suggested by A. Treisman (personal communication, 1991). Because both sets of data (target-present and target-absent) are divided by the same number, the relationship of target-present to target-absent conditions changes less with this correction. Instead, it results in steeper slopes when there are many errors of omission (there were always few errors of commission). Statistical analyses for both corrections are shown in Table 2, and slopes and slope ratios are presented in Table 4.

There was little effect of either correction on SLs because there were very few errors (Figures 3B and 3C). Thus, the hypothesis that search is parallel is still supported. For Ts, Correction 1 results in slopes that were approximately equal (set size $\times$ target presence interaction

Figure 7. Reaction times (in milliseconds) as a function of set size for Experiment 3B. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for M in Ss. Right graphs (D, E, F) are data for S in Ms.

was not significant), which suggests an exhaustive, serial search (Figure 3E, Table 4). Correction 2, however, provides data that support a self-terminating, serial search (Figure 3F). The target-absent to target-present slope ratio is nearly 2 (Table 4), and there is a significant increase in RT with set size. There is also a significant interaction of set size $\times$ target presence.

Table 5 presents search rates (the mean of target-present and target-absent slopes) for each analysis, the increase (or decrease) in minimum RT, and the slopes for *SD* for target-present and target-absent trials. Minimum RT did not increase with set size for SLs, but there was a small increase in minimum RT with set size for Ys and a large increase for Ts, consistent with serial search.

For all three target types, there was equal or less variability with increase in set size (shallower slopes; Table 5) for the target-present condition than for the target-absent condition, the opposite of what would be expected in a serial, self-terminating search.

The data for Ys (Figure 3G) are more complicated to analyze. There was a small increase in RT with set size that did not reach significance after Correction 1 (Figure 3H) but was significant after Correction 2 (Figure 3I). Furthermore, there were longer RTs if there was no tar-

get present. In addition, the set size $\times$ target presence interaction did not reach significance (Table 2), suggesting that the search was not self-terminating even though the slope ratio was greater than 2:1 for uncorrected data and after Correction 2. However, it is important to be cautious in interpreting slope ratios when the slopes are shallow. With shallow slopes, a relatively small change in a data point will result in a large change in the slope ratio, whereas with a steep slope, the same small change will have little effect on that slope ratio.

Further criteria (Townsend & Ashby, 1983) suggest that search for Ys may be capacity limited. Limited-capacity search is supported inasmuch as there was an increase in RT with set size, and minimum RT increased with increasing set size for target-present data (Table 5). An argument against serial search may be made from the *SDs*. They did not increase more with set size for target-present than for target-absent conditions.

However, it is possible that search for Ys is neither strictly parallel nor serial because the Ys differ from each other in two ways. While the SLs differ from one another only in line orientation, and the Ts differ from one another only in line arrangement, the Ys differ in both ways. It is possible that observers used two different strategies:

Figure 8. Reaction times (in milliseconds) as a function of set size for Experiment 3B. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for M in Ws. Right graphs (D, E, F) are data for W in Ms.

(1) target presence was determined primarily by a parallel search for a difference in line orientation, and (2) target absence was determined primarily by serial search for a line-arrangement difference. However, another aspect of the data argues against such a dichotomy between target-present and target-absent trials, because there was an increase in RT with set size for the target-present data. It is possible that these two strategies both operate, but in a different proportion of target-present and target-absent trials.

If two different strategies are used in search for Ys, one might find a bimodal distribution in RTs. To consider this possibility for Ys, frequency distributions were examined for each observer separately. A frequency distribution was plotted separately for each condition for each observer, resulting in 24 trials in each distribution. A visual inspection of the plots showed that data from 2 of the 8 observers fit the prediction, particularly for target-absent trials. For the other 6 observers, distributions appeared to be unimodal, with individual means falling between the individual means for SLs and the individual means for Ts. Of course, 24 trials may be insufficient to estimate the modality of a distribution. Therefore, it was

not possible with the present data to accept or reject the mixed-search-strategy hypothesis on the basis of individual RT distributions. We conclude that the processes that are involved in search for Y stimuli are not as easily understood as are the processes involved in search for SLs and Ts.

Experiment 2: Lines, OTs, and OYs (Figure 4)

Again, RTs differed significantly depending on the target type, the set size, and the presence or absence of the target (Table 6). The only significant effects for errors were in the interactions of target type $\times$ set size, set size $\times$ target presence, and target type $\times$ set size $\times$ target presence (Table 3). The three-way interaction is support for the increase in errors with set size for target-present trials for OTs and OYs, but not for LIs (Figures 4D, 4G, and 4A, respectively).

As with SLs, perception of a disparate horizontal or vertical line showed a pattern typical of parallel search, since there was no effect of set size or of target presence (Figure 4A). There was an interaction of set size $\times$ target presence, which was due to a crossover of target presence and target absence between set sizes of 2 and 9. Al-

Table 8
Analysis of Variance for Experiment 3B

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Target type	1,7	35.61†	49.81†	50.32†
	Character	1,7	1.25	10.57	20.23*
	Set size	2,14	42.85‡	62.77‡	62.14‡
	Presence	1,7	29.98†	9.41	24.97*
	T×C	1,7	0.01	7.16	10.44
	T×S	2,14	22.50‡	44.63‡	38.87‡
	C×S	2,14	0.36	7.12*	12.60†
	C×P	1,7	33.77†	64.55‡	31.37†
	S×P	2,14	8.81*	0.59	9.24*
	T×C×P	1,7	42.07†	109.18‡	46.99†
	C×S×P	2,14	14.19†	41.55‡	12.67†
	T×C×S×P	2,14	18.35‡	30.74‡	18.11‡
M in Ss (A)	Set size	2,14	58.55‡	86.98‡	56.18‡
	Presence	1,7	0.10	19.31*	0.07
	S×P	2,14	0.32	13.94†	0.36
S in Ms (B)	Set size	2,14	27.40‡	22.03‡	23.62‡
	Presence	1,7	94.22‡	96.42‡	98.02‡
	S×P	2,14	34.18‡	11.86†	46.76‡
M in Ws	Set size	2,14	27.80‡	18.66‡	17.73‡
	Presence	1,7	8.03	5.26	7.88
	S×P	2,14	3.77	1.01	4.34
W in Ms	Set size	2,14	12.50†	10.51*	11.27*
	Presence	1,7	27.72*	24.61*	27.31*
	S×P	2,14	6.32	3.41	6.33

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions. Interactions that are not listed did not reach .01 statistical significance. * $p < .01$. † $p < .001$. ‡ $p < .0001$.

though this interaction was significant in all three analyses, it may be unimportant, unless the decrease in RT with set size for target-present trials is due to a supercapacity for these targets.

For OTs, similar to Ts, search fit a typical serial pattern, with a large increase in RT with increases in number of distractors and an increase that was twice as great when no target was present (Figure 4D). Set size × target presence interacted significantly. Thus, data for OTs also suggest a serial, self-terminating search.

For OYs, also, there was an effect of an increase in set size. This was a much larger increase than for Ys. There was a greater effect of target presence on OYs than on OTs. These effects were due to longer RTs for target-absent trials than for target-present trials, similar to effects for Ys.

Correction for errors had little effect on LIs because of the small proportion of errors. In contrast, Correction 1 resulted in a reduction of the effects of target presence, and the interaction of set size × target presence was no longer significant for OTs. Correction 1 data for OTs were similar to those for Ts; the slopes were approximately equal (no set size × target presence interaction), which suggests an exhaustive search (Figure 4E, Table 6). However, this interaction was significant after Correction 2, similar to that of the uncorrected data (Figure 4F). The effects of correction for errors for OYs were similar to those for OTs (Figures 4H and 4I).

Other data support a serial search for OT in that there was close to a 2:1 target-absent to target-present slope ratio with either uncorrected data or with Correction 2 (Table 4) and an increase in minimum RT with set size (Table 5). Slopes for *SD* are consistent with a serial search because the slope was greater for target-present trials than for target-absent trials.

For OYs, there were significant increases in minimum RT with set size, and *SD* did not increase more for target-present trials than for target-absent trials, similar to the data for Ys. In contrast to Ys, however, there were significant set size × target presence interactions in either the uncorrected or the Correction 2 analyses. Correction 1 increased target-present slope and decreased target-absent slope. In contrast, Correction 2 increased the target-absent slope as well as the target-present slope. The resulting slope ratio was somewhat greater than 2:1, but not as high as the ratio for uncorrected data. It is possible that when the Y is placed obliquely, as with upright Ys, either parallel or serial search can be used; but with OYs, the serial search is primarily used and relatively little parallel search is used, whereas for Ys, there is a greater proportion of parallel search.

Experiment 3A: Ms and Es (Figures 5 and 6)

For the target types in which both sets of stimuli included a character with three line endings and one with two line endings, there was an asymmetry in the effects

Figure 9. Reaction times (in milliseconds) as a function of set size for Experiment 4: curves. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for a curved line in angles. Right graphs (D, E, F) are data for an angle in curves.

of set size that depended on which character was the target. These two target pairs (M vs. S [referred to as (A) or (B) for Experiment 3A or Experiment 3B] and E vs. S) were remarkably similar. For M in Ss(A) or E in Ss, slopes for target-present and target-absent trials were nearly equal, whereas for S in Ms(A) or S in Es, there were steeper slopes for target-absent trials than for target-present trials (Table 4). These effects were shown to be significant (target character $\times$ set size $\times$ target presence interaction; Table 7). These slopes suggest an exhaustive search for M in Ss(A) or E in Ss, but a self-terminating search for S in Ms(A) or S in Es. Because of the increase in RT with set size, either search may be serial.

Error data revealed significant increases in errors with set size, which were larger for M in Ss(A) or E in Ss than for S in Ms(A) or S in Es.

Changes after correction for errors were dependent on the correction method. Correction 1 resulted in reduced effects of target presence, a significant interaction of target character $\times$ set size, and loss of significance of set size $\times$ target presence. In contrast, the statistical analysis after Correction 2 was similar to that of the uncorrected data, but showed much steeper slopes for M in Ss(A) or E in Ss and for target-absent S in Ms(A) or S

in Es trials (Figures 5C, 6C, 5F, and 6F, respectively). While Correction 1 resulted in an inexplicable crossover of greater increase for target-present trials than for target-absent trials for M in Ss(A) or E in Ss (Figures 5B and 6B), Correction 2 gives further support to the exhaustive pattern for M in Ss(A) or E in Ss and the self-terminating pattern for S in Ms(A) or S in Es.

All of these conditions resulted in large increases in minimum RT with set size. The slopes for standard deviation were more than 1 msec larger for target-present trials than for target-absent trials for M in Ss(A) or E in Ss, but were not for S in Ms(A) or S in Es.

Experiment 3B: Ms and Ws (Figures 7 and 8)

For the targets in which one set had characters with two or three line endings (M vs. S) and the other set had characters with three line endings (M vs. W), there was a large difference between the target types (Table 8). The M versus S data closely replicated the data for M versus S in Experiment 3A. This suggests that different observers cannot account for differences between types of targets in these tests inasmuch as most of the observers were tested in only one of the groups. When M in Ss(B), M in Ws, or W in Ms were targets, set size $\times$ target pres-

Table 9
Analysis of Variance for Experiment 4: Curve

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Character	1,8	15.20*	19.16*	19.42*
	Set size	2,16	19.85‡	24.33‡	29.56‡
	Presence	1,8	50.50‡	18.27*	46.40‡
	C × S	2,16	10.50*	20.18‡	15.69†
	S × P	2,16	5.93	2.96	5.89
CU in AN	Set size	2,16	23.98‡	31.03‡	28.09‡
	Presence	1,8	25.09†	6.04	20.38*
	S × P	2,16	4.05	4.52	4.16
AN in CU	Set size	2,16	8.30*	5.29	6.90*
	Presence	1,8	26.45†	17.79*	26.99†
	S × P	2,16	2.91	0.83	2.84

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions. Interactions that are not listed did not reach .01 statistical significance. * $p < .01$. † $p < .001$. ‡ $p < .0001$.

ence was not significant, but when S in Ms(B) were targets, RT increased with set size for target-absent trials more than for target-present trials. There were big differences between M in Ss(B) and S in Ms(B) (Figure 7), but data for M in Ws or W in Ms showed no asymmetry (Figure 8). Slopes were shallower for M versus W than for M versus S (Table 4), and slope ratios were large for S in Ms(B), M in Ws, and W in Ms but were at unity for M in Ss(B), as they were for M in Ss(A).

There were increasing numbers of errors of omission (on target-present trials) with set size, particularly when M in Ss(B) were the targets (Figure 7A, Table 3). Thus, for errors, as well as for accuracy, there was an asymmetry depending on which character was the target.

After Correction 1, the effect of target presence was marginally significant ($p = .018$). Interactions were altered: set size × target presence was no longer significant, target type × target presence × set size was reduced, and significance levels were higher for target character × set size, target character × target presence, target type × target character × target presence, and target character × set size × target presence.

After Correction 2, statistics were similar to those on the uncorrected data, but slopes were steeper, particularly for M and S comparisons (Table 4). Slope ratios did not change appreciably. With either correction, there was an asymmetry depending on the target character for M versus S, but not for M versus W. Thus, based on slopes and slope ratios, S in Ms(B), W in Ms, and M in Ws could be considered to result in serial, self-terminating searches or, alternatively, the pattern could be due to parallel search with serial recheck on some target-absent trials. M in Ss(B) slope ratio is consistent with either serial, exhaustive or parallel, limited-capacity search. The steep slope, however, is more indicative of serial, exhaustive search.

There was an increase in minimum RT with set size for all four target types (Table 5), which is also consistent with self-terminating search. However, only the slope for standard deviations for M in Ss(B) was greater for

target-present trials than for target-absent trials. Thus, SD provides another measure where there is an asymmetry between M in Ss and S in Ms, but consistency for M in Ws and W in Ms.

Considering Experiments 3A and 3B, for both M versus S and E versus S, when the character with two line endings (S) was the target, the transformations had little effect (Figures 5E, 5F, 6E, 6F, 7E, and 7F, Table 4). On the other hand, when the target was a character with three line endings in a field of characters with two line endings [E in Ss or M in Ss(A and B)], Correction 1 resulted in a crossover so that there was a much greater increase with set size for target-present trials than for target-absent trials (Figures 5B, 6B, and 7B). Correction 2 showed slope ratios near unity suggestive of exhaustive search (Figures 5C, 6C, and 7C). Variability increased more with set size for target-present trials than for target-absent trials for these targets in Experiments 3A and 3B (Table 5). The three groups were also consistent with regard to minimum RT: there were increases in minimum RT with set size for all of them. Further consideration of search types will be presented below.

Experiment 4: Curves (Figure 9)

Data were analyzed separately for curves and for the three colors. For *curves* versus *angles*, there was an increase in RT with increasing set size and more increase on target-absent trials than on target-present trials (Table 9). Again, there was an asymmetry between which character was the target and which characters were distractors. There were longer RTs and more increase with set size when the target was a curve than when the target was an angle. Slope ratios indicate that search may be serial, self-terminating for both targets (uncorrected data for curve; Table 4).

There were also large effects on the error data (Table 3). There was an increase in RT with increasing set size, more increase on target-present trials than on target-absent trials, and particularly more increase with set size

Figure 10. Reaction times (in milliseconds) as a function of set size for Experiment 4: colors. Graphs are constructed as in Figure 3. Left graphs (A, B, C) are data for red or green targets. Center graphs (D, E, F) are data for red or yellow targets. Right graphs (G, H, I) are data for green or yellow targets.

for target-present trials. There were more errors and more increase with set size on target-present trials when the target was a curve than when the target was an angle. The errors were mostly of omission in finding a curve among a large field of angles.

Asymmetry of the targets is also shown after data correction to adjust for errors. With Correction 1, there were longer RTs for curves in angles than for angles in curves and greater increase in RT with set size (Figures 9B and 9E). The interaction of target character $\times$ set size indicates that there was more increase with set size for curves as targets than for angles as targets. There were no differences between target-absent and target-present trials for curve targets at the largest set size.

Statistical analysis shows the same effects after Correction 2 as for the uncorrected data. However, slopes are steeper, particularly for curve in angles, even though slope ratios were similar (Table 4, Figures 9C and 9F). The asymmetry is also shown with minimum RT, where there is a much larger increase with set size for curves than for angles (Table 5). In contrast, slopes for *SD* are shallower for target-present trials than for target-absent trials for either case. Thus, a clear picture of the type of search is not presented by the data.

Experiment 4: Color (Figure 10)

Differences were revealed for target type (RG, RY, and GY) and target presence (Table 10). There were slower responses to GY than to either RG or RY, and for GY there were longer RTs for target-absent trials than for target-present trials. In addition, there were interactions of target type $\times$ set size, with more increase on GY with set size. The flat slopes for RG and RY suggest a parallel search (Figures 10A and 10D). The increase in RT with set size for GY indicates a difference from the other color discriminations (Figure 10G). A serial search is not indicated for any of these discriminations because of the slope ratios that are equal to or less than unity (Table 4). Perhaps a parallel, unlimited-capacity search is used for RG and RY, but a parallel, limited-capacity search is used for GY.

There were very few errors in the present experiment. The only significant effect was an interaction of set size $\times$ target presence (Table 3).

In this experiment, increases in minimum RT were not useful in deriving a search type because RG showed a decrease, whereas RY and GY showed small increases. Slopes for *SD* do separate in a manner similar to slopes for RT, because only for GY is the slope of *SD* for target-

Table 10
Analysis of Variance for Experiment 4: Color

Targets	Effect	df	F		
			Not Corrected	Correction 1	Correction 2
Overall	Target type	2,14	27.04‡	26.44‡	24.55‡
	Set size	2,14	3.57	1.52	4.62
	Presence	1,7	18.03*	7.74	18.74*
	T×S	4,28	8.75‡	8.65‡	8.57‡
	T×P	2,14	13.56†	7.62*	13.57†
	S×P	2,14	3.54	14.48†	3.03
RG	Set size	2,14	1.36	3.20	0.36
	Presence	1,7	0.25	0.30	0.34
	S×P	2,14	2.03	2.64	10.89*
RY	Set size	2,14	1.06	4.22	1.14
	Presence	1,7	0.36	0.07	0.30
	S×P	2,14	10.63*	15.29†	2.01
GY	Set size	2,14	8.68*	6.83*	9.87*
	Presence	1,7	27.67*	13.86*	27.13*
	S×P	2,14	0.01	3.82	0.04

Note—Correction 1: Median RT divided by proportion correct, where proportion correct is computed separately for target-absent and target-present conditions. Correction 2: Median RT divided by proportion correct for *target-present* trials in both target-absent and target-present conditions. Interactions that are not listed did not reach .01 statistical significance. * $p < .01$. † $p < .001$. ‡ $p < .0001$.

present trials at least 1 msec steeper than that for target-absent trials.

Separate analyses for each of the three color comparisons showed that there were no significant effects in the uncorrected data for RG discrimination. For RY discrimination, RT data had a significant interaction of set size × target presence that was somewhat stronger after Correction 1 but was nonsignificant after Correction 2. This interaction was due to a decrease in slope for target-absent trials. For GY discrimination, RTs increased significantly with set size and were longer for target-absent trials than for target-present trials. These did not interact.

The set size × target presence interaction for RG after Correction 2 was due to a slight decrease in RT as a function of set size for target-absent trials. This was similar to the set size × target presence interaction for RY with uncorrected data and after Correction 1.

One major difference in GY discrimination was that the green and yellow used here were more similar in both luminance and hue than were the other two comparisons (Table 1) and, consequently, the discrimination was more difficult. This point will be explored further below.

Summary

The purpose of these complex analyses is to determine the nature of the search process for different targets. Some of the targets studied appear to elicit a parallel, unlimited-capacity search (SLs, LIs, RG, RY), while some of the targets fit most of the criteria of serial, self-terminating search [Ts, OTs, OYs, S in Ms(A and B), S in Es]. The other targets seem to rank somewhere between these extremes.

For the simplest cases, uncorrected slope ratios may be sufficient to explain what is occurring during search. For the more complex cases, however, multiple criteria may lend some insights. Of course, it may not be possi-

ble to determine with certainty what search strategy is used for a particular target because (1) different strategies may be used on different trials in searching for the same target and (2) strategies may change within a trial. The second possibility may occur more often when the target is not found readily.

When the targets are ranked separately by the different measures, the resulting rank orders differ (Tables 4 and 5). These differences in rank order may indicate that search is not carried out using the same strategies for all target types. There may be qualitative differences in the processes used in different searches.

In Table 11, the targets are ordered approximately according to arbitrary classes, to which a number from 1 to 5 was assigned. The number represents increasing similarity to a limited-capacity, serial, self-terminating search. We use the term "classes" as a way of distinguishing separate groups without assuming that observers necessarily used the same or different strategies for these searches. Column 2 of Table 11 contains the rank order for average search rates for uncorrected data (i.e., the mean of the slopes for target-present and target-absent trials). This rank order tends to increase with similarity to a limited-capacity, serial, self-terminating search, although not consistently for the higher ranks. The remaining five measures were categorized to provide qualitative estimation of important differences within each measure.

The classes of search (defined below) present some difficulties, but targets for which there was a concordance of the different measures were grouped together. For each of these classes, we have provided suggestions for possible search strategies, but it is not assumed that the same strategy of search is necessarily used for all targets within each class. Obviously, the assignment of target types on the various measures in Table 11 is somewhat arbitrary. For example, in this classification process, only uncor-

Table 11
Visual Search Analysis

Targets	Search Rate Rank ^a	2:1 Absent-to-Present Slope ^b	Increased RT with Set Size ^c	Set Size by Target Presence ^d	Minimum RT Increased with Set Size ^e	SD + > SD - ^f	Class ^g
Red/Yellow	1.5	—	—	—	+	—	1
Red/Green	1.5	—	—	—	—	—	1
Lines	3	—	—	—	—	—	1
Slants	4	—	—	—	—	—	1
Green/Yellow	5.5	—	+	—	+	+	2
Ys	5.5	++	+	—	+	—	3
Angle in curve	7	++	+	—	+	—	3
W in Ms	8	++	+	—	+	—	3
M in Ws	9	++	+++	—	++	—	3
Curve in angle	11	+	+++	—	++	—	3
M in Ss (A)	14	—	+++	—	++	+	4
E in Ss	16	—	+++	—	++	+	4
M in Ss (B)	17	—	+++	—	++	+	4
Oblique Ys	10	+	+++	+++	+	—	5
Oblique Ts	12	+	+++	+	++	+	5
S in Ms (A)	13	++	+++	+++	++	—	5
Ts	15	+	+++	+++	++	—	5
S in Es	18	+	+++	+++	++	—	5
S in Ms (B)	19	++	+++	+++	++	—	5

^aRank order of mean target-present and target-absent slopes based on uncorrected data. ^bRatio of target-absent to target-present; — is used to indicate a ratio of <1.1, + indicates ratio 1.9–2.4, ++ indicates ratio >2.7; based on uncorrected data. ^cStatistically significant increase in RT with set size; — indicates $\chi^2(2,14) = <2.0$, n.s.; + indicates $\chi^2(2,14 \text{ or } 2,16) = 4.0\text{--}13.0$, $p < .01$; +++ indicates $\chi^2(2,14 \text{ or } 2,16) = >23.0$, $p < .0001$. ^dMore increase with set size for target-absent than for target-present; — indicates $\chi^2(2,14 \text{ or } 2,16) = <7.0$, n.s.; + indicates $\chi^2(2,14) = 11.0$, $p < .01$; +++ indicates $\chi^2(2,14 \text{ or } 2,16) = >16.0$, $p < .0001$. ^e— indicates decrease in minimum RT for target-present trials; + indicates small increase; ++ indicates large increase. ^fStandard deviation for target-present increased with set size at least 1 msec more than standard deviation for target-absent. ^gDefined in Results section.

rected slopes were used. If data for either correction were used instead, a number of points would change. For instance, if Correction 1 were used, Ts would not have a 2:1 target-present to target-absent slope. Thus, it would be possible to arrive at different classifications if different criteria were used.

Search class 1: Unlimited-capacity, parallel, exhaustive search. The first four target pairs in Table 11 do not have a 2:1 target-absent to target-present slope ratio, show no significant increase in RT with set size, and have no greater increase for target-absent trials than for target-present trials, and variability does not increase with set size more for target-present trials than for target-absent trials. RY has a small increase in minimum RT with set size. This increase is probably not meaningful because there was a negative search rate due to a negative target-absent slope. LIs and RY have significant set size $\times$ target presence interactions (Tables 6 and 10, respectively). In the case of RY, the interaction is reversed so that target-present trials have longer RTs than do target-absent trials, and for LIs, the interaction is at least partially due to a decrease with set size for target-present trials. (Note that in Table 11, only interactions due to more increase with set size for target-present trials than for target-absent trials are reported.) In spite of these inconsistencies, one may speculate that search for targets placed in class 1 is primarily parallel with unlimited capacity. Note that there is some supercapacity for these four target types: on the target-absent trials for RY and RG and on the target-present trials

for SLs and LIs. These negative slopes may be due to distractor grouping when more distractors are present (Bacon & Egeth, 1991; Duncan & Humphreys, 1989), to local comparisons (Green, 1991), or to comparative coding rather than single-target coding (Treisman & Gormican, 1988).

Search class 2: Limited-capacity, parallel, exhaustive search. GY is different from all the rest of the target types. The significant increase in RT with set size indicates a limited capacity. Minimum RT increases with set size, and the variability for target-present trials increases more with set size than does the variability for target-absent trials, which is consistent with a self-terminating search. However, an exhaustive search is suggested by the slope ratio, which is at unity or less for all three data analyses. Thus, the evidence is strongest for classifying GY as a limited-capacity, exhaustive, parallel search.

Search class 3: Mixed strategies that could include limited-capacity, exhaustive or self-terminating, serial search. The next five target types (Ys, angle in curves, W in Ms, M in Ws, and curve in angles; Table 11) have 2:1 or greater target-absent to target-present slope ratios, significant increases in RT with set size, and increases in minimum RT with set size. These characteristics suggest a serial, self-terminating search. However, the set size $\times$ target presence interaction did not reach our strict criterion for significance (.01) for these targets. Nevertheless, this interaction approached significance for all five targets (ps ranging from <.02 to <.09).

Figure 11. Display for M target in S distractors (top screens) and S target in M distractors (lower screens) for 24 characters with target present (left) and target absent (right).

The increase in minimum RT could indicate limitations on capacity, perhaps due to occasional use of a different strategy. As stated above, in the case of Ys, different strategies could be based on line arrangement rather than on line orientation. Another argument against a strict serial search is that the variability did not increase with set size more for target-present trials than for target-absent trials for class 3 targets. Mixed strategies could also be used for all targets in this class.

Search class 4: Limited capacity, exhaustive, serial search. For M in Ss and E in Ss, significant increases in RT with set size indicate limited capacity. Also, the fact that slope ratios are near unity, the lack of set size $\times$ target presence interactions (these did not even approach significance), and the variability distribution suggest an exhaustive search. However, parallel slopes for target-present and target-absent trials can be self-terminating if search is left to right and processing time increases with set size (fixed-path, serial, self-terminating search; Townsend & Ashby, 1983). If this is what occurs, the search for these targets could be fixed-path, serial, self-terminating. Increases in minimum RT with set size for the three target types are also consistent with a serial, self-terminating search.

Search class 5: Limited-capacity, self-terminating, serial search. Six target types with slow search rates [OYs, OTs, Ts, S in Ms(A and B), and S in Es] seem to fit most of the criteria for a limited-capacity, self-terminating, serial search. They have 2:1 or greater slope ratios, large increases in RT with set size, significant interactions between set size and target presence, and large increases in minimum RT with set size. OYs may be misplaced here, in that several measures were similar to those of Ys, and as stated in the Results, OY data may be the result of mixed search strategies.

The data are not as consistent for our measures of variability. OTs show more increase in variability with set size for target-present trials than for target-absent trials.

However, for the other targets in this class, the variability for target-present trials was not larger than the variability for target-absent trials. The inconsistency in the variability measures may be due to problems inherent to the measure. Reports for conjunction searches show an inconsistency in increases in variance (Treisman, 1991; Ward & McClelland, 1989). Treisman suggested that differences in the results reported in these two studies may have been due to the fact that Ward and McClelland required their observers to alternate between two search tasks, but Treisman did not. In the present case, the within-block randomization of the target may have altered the pattern of variability for the more difficult targets.

With this complex analysis, five classes of search have been suggested. It can be seen that some of these classes of search are neither clearly parallel nor strictly serial. A few targets show all of the criteria for an unlimited-capacity, parallel search, and a few fit most of the criteria for limited-capacity, self-terminating, serial search. What is probably most important is that these five classes of search would not have been uncovered by analysis of any one measure, or even combinations of two or three measures. All of the measures were required.

DISCUSSION

In this paper, several different types of targets were tested in a visual-search task to determine whether they would separate neatly into a parallel-serial distinction or whether it would be more informative to look for other search strategies as well. To make a careful assessment of the type of search that was used for each target type, data were analyzed by multiple methods. The targets did not sort into a simple dichotomy, but rather were grouped according to six measures into five classes that might represent different search strategies. Even though the assignment of targets to classes was somewhat arbitrary, this analysis illustrates the complexity of interpretation of data from visual-search experiments.

Consistency with Past Research

Targets similar to some of those used in these experiments were also used in previously published studies. In these cases, the present data were generally consistent with previous data. For instance, a tilted T target was easily discriminated from upright Ts or Ls (Beck, 1966). This discrimination was likely made on the basis of line orientation, as were our SL and LI targets. In contrast, an L among upright Ts did not "pop-out" (Beck & Ambler, 1972). Such a discrimination is similar to the sideways Ts that we used. The sideways Ts have the advantage of sharing the same conjointing of vertical and horizontal lines so that no angles are created at the perimeter of the character.

Some of the feature targets that were used resulted in typical parallel searches; for instance, RG, RY, and LIs of different orientations. Some of the more controversial "features," however, did not result in a simple parallel search. Some of them, such as GY (*target-distractor dis-*

criminability) and curves/angles and S in Ms/M in Ss (*asymmetries*), will be discussed below.

None of the differences in the number of line endings resulted in typical parallel search. Search for W in Ms or the reverse was more rapid and more similar to a parallel search than M versus S or E versus S searches, even though the former targets (M and W) have the same number of line endings and the latter (M or E and S) have different numbers of line endings. This finding would not be predicted if number of line endings is a feature (Julesz, 1982).

Data Transformation to Correct for Errors

Data were transformed by use of two separate corrections for errors to correct RT for the possibility that incorrect trials were actually trials that were aborted early. If these trials had been correct, RTs would have been longer. In Correction 1, RT for target-present trials was divided by the proportion of correct target-present trials, and RT for target-absent trials was divided by proportion of correct target-absent trials. In Correction 2, both target-present and target-absent trials were divided by proportion correct for target-present trials. Which of the data analyses is the most appropriate?

One of the plans for this research was to determine whether targets would group simply into parallel and serial search classes. This did not occur with any of the analyses. For each analysis, concurrence in the different measures was examined and the targets were grouped according to the best concurrence. For Correction 1, this grouping resulted in six classes of search types, which had poor consistency within classes. With uncorrected data or with Correction 2, the targets grouped into the same five classes shown in Table 11. In this case, concurrence for the measures within each class was quite good. With either correction, rank order for search rate did not approximate the class order in that the highest rank orders were for class 4 targets. Rank order of search rate for the uncorrected data was more consistent with the other measures than was search rate based on the corrections.

Townsend and Ashby (1983) provide good arguments for considering errors; however, there are both theoretical and empirical reasons to prefer Correction 2 over their suggested correction (Correction 1). Consider yourself as an observer watching a display. If you do not locate a target, both target-present and target-absent displays appear the same to you. It is only upon discovery of a target that the target-present display appears different. Thus, if you halt a trial with a negative response, no matter how many characters you have examined, you only make an error on target-present trials. Therefore, correcting both target-present and target-absent trials with proportion correct for target-present trials seems more appropriate theoretically. Empirically, we found better grouping of the targets with Correction 2.

Of course, it is also possible that only target-absent trials should be corrected. However, such a correction ignores the fact that target-present trials that were in error would have produced longer RTs if they had been correct since the observer would have searched additional characters to find the target. Therefore, this correction was not used in the present work.

Interestingly, the results with Correction 2 and uncorrected data were not much different, although in some cases slope rates were increased considerably (see Figures 5, 6, and 7, particularly). Also, slope rates for the uncorrected data were more consistent with the grouping into classes than were slope rates after Correction 2. Therefore, we used the more straightforward, uncorrected data for placing targets into classes.

Interpretation of Various Measures of Search

A survey of the search-rate data shows that the stimuli do not divide into a simple dichotomy between targets for which only parallel search was used and other targets with a clearly serial search. Instead, they appear to represent samples chosen from a continuum of search rates, which could be interpreted to represent a continuum of attention allocation. This interpretation is consistent with previous explanations of search-task data (Beck, 1982; Duncan & Humphreys, 1989; Quinlan & Humphreys, 1987).

It appears that analysis of only target-present slopes is insufficient to explain the allocation of attention in the visual searches used here. These slopes vary from -1.0 for LIs to 22.5 for M in Ss(A). There is no clear indication of a cutoff point to separate "feature" targets from targets that require attention. Also, there is little relationship between slope and target-absent to target-present ratios [$r(17) = .24, p > .10$]. If one uses the target-present slopes that result after correction for errors, there is some evidence for a possible dichotomy. The slopes for 12 of the comparisons are under 10, and the other 7 slopes are above 16. However, of those 7 comparisons, the target-absent to target-present ratio is less or near unity for 4 of the comparisons. Only for Ts, OTs, and S in Es is there approximately two times as great a slope for target-absent trials as for target-present trials. Thus, using only slopes to determine serial search would eliminate three of the six targets from class 5.

Target-Distractor Discriminability

Our data also are consistent with the principle that search efficiency decreases with increasing similarity between the target and distractors (Duncan & Humphreys, 1989). In the present research, the difference in search times between GY and the other color discriminations may reflect the greater difficulty of the GY discrimination, consistent with previous data (Carter, 1982; Moraglia, Maloney, Fekete, & Al-Basi, 1989; Nagy & Sanchez, 1990). Differences in difficulty are reflected in longer RTs in search for GY than for RG or RY, even for two-

character displays (Figure 10). Of course, it has been known for some time that increasing the similarity of target and distractors has a detrimental effect on RT (Farmer & Taylor, 1980). This is true even if no form discrimination is involved.

In addition, results from other studies of visual search also show considerable variation with small changes in the stimuli. For instance, Treisman and Gormican (1988) showed that when a vertical line or an 18° oblique line were searched in a field of 6 or 12 characters of the opposite type, search times were much longer when the vertical line was the target than when the oblique line was the target. That experiment differed from the present one (SLs and LIs) in the amount of angular differences between the two types of lines: only 18° in Treisman and Gormican and 90° in the present experiment. With the stimuli used here, there was no asymmetry for line-orientation targets. Although Treisman (1986) suggested that early vision may encode tilt but not verticality, she did not test vertical and horizontal targets.

The disparity in slope rates for 18° (Treisman & Gormican, 1988) versus 90° angular differences (our data) in line orientation is another indication that task difficulty can affect search strategy (Duncan & Humphreys, 1989). In addition, the slope of RT as a function of set size correlated highly with the RT for a display of two characters, a measure that may be considered to be a measure of discriminability [$r(17) = .699, p < .01$]. Thus, in this task, the slopes of the RT function reflect both target-distractor discriminability and the need for attention.

It is possible that target-distractor discriminability is responsible for some of the separation of classes in the present data. Search in class 2 (GY) may only differ from class 1 in decreasing the amount of capacity demanded by the more difficult search. Similarly, class 5 may also differ from class 3, primarily because of increased difficulty of search. Search rates are slower for five of the six targets in class 5 than for the five targets in class 3. This suggests that both class 3 and class 5 represent data from serial, self-terminating searches, but class 5 requires more of the limited capacity than does class 3. However, as stated above, other evidence suggests that class 3 search may be composed of both exhaustive and self-terminating strategies.

Asymmetries

The fact that all of our measures do not correlate suggests that, although there is a continuum of search rates, there may be qualitative differences in the way that different searches are accomplished. Perhaps there are different processes used for some kinds of searches than for others. Some possible examples are indicated by the asymmetry between angles and curves and between M in Ss or E in Ss and S in Ms or S in Es.

Angles in curves have shallower slopes (Table 4; faster search rates, Table 5) and less increase in RT with set size (see Figure 9) than do curves in angles; angles in curves also have a greater than 2:1 target-absent to target-present slope ratio, whereas curves in angles only have

a 2:1 target-absent to target-present slope ratio with uncorrected data. In spite of these differences, both targets were placed in class 3. Here again, differences in search may only be due to differences in the target-distractor discriminability, resulting in greater demands on the limited capacity for curves in angles than for angles in curves. It is possible, of course, to postulate feature differences, such as the sharp vertex of the angle (suggested by A. Treisman, personal communication, July 18, 1991). On the other hand, search may vary from exhaustive to self-terminating from trial to trial.

Target-present slopes were more than twice as large when searching for M in a field of Ss than the reverse. There were even greater differences if the corrected data were used (slopes for M in Ss were over five times as great as slopes for S in Ms; Table 4). In addition, S in Ms and S in Es (Figures 5, 6, and 7), in comparison to E or M in Ss, have 2:1 or greater target-absent to target-present slopes, interactions of set size $\times$ target presence, and no appreciably greater increase in variability with set size for target-present trials than for target-absent trials; whereas M or E in Ss have no 2:1 target-absent to target-present slopes, interaction of set size $\times$ target presence does not reach significance, and there is more increase in variability with set size for target-present trials than for target-absent trials. The same pattern of results was obtained in two different tests using Ms and Ss and in one test using Es and Ss, so the pattern is highly reliable.

What could be the cause of these asymmetries? First of all, it should be noted that for the asymmetries discussed, observers could not have developed a separate strategy based on knowledge of the target because the two possible targets were randomized within blocks of trials. Additionally, it is obvious that differences in target-non-target similarity cannot be a factor. What about differences in the tendency of the characters to cluster together when they are distractors (Treisman & Gormican, 1988)? The target-present and target-absent conditions are illustrated in Figure 11. It is easy to see that the S is more readily found than the M, and it is possible that the distractor Ms cluster more strongly than the distractor Ss. Perhaps the distractors are rejected rather than the target facilitated, as suggested by Treisman and Sato (1990).

Another possibility is that observers are searching for a particular feature that is present in one target but not in the other. It has been suggested that asymmetries exist because it is easier to find the presence of a feature than its absence (i.e., a circle with a line in a field of circles compared with a circle in a field of circles with lines; Treisman & Souther, 1985). If search for a target is based on the perception of one or more features, then it should be possible, prior to testing, to specify the feature or features responsible for differences in search strategy. This is difficult to do in the present case. For example, if observers were looking for the longer horizontal line in the M (size feature), the M should have been easier to find than the S, contrary to what was observed (Figures 5, 6, and 7). Similarly, if more unconnected line endings enhance target salience, then why is the M harder to find

than the S? Another possible feature is closure. Although neither M nor S are closed characters, subjectively S may appear more closed than M since the two gaps of the M appear contiguous. This could be the feature that allows easier search for an S. Or the only upward-pointing, free line ending may make the S more salient (suggested by A. Treisman, personal communication, 1991).

However, these possibilities are only conjectures made after data collection. Such a method of defining features seems circular. Even if an explanation of this kind could be constructed for this asymmetry, it may not predict further results obtained with these same distractors. For instance, it is shown in Figures 5 and 7 for uncorrected data that, even though Ms are harder to find than Ss, it is nevertheless easier to *reject* a screen of Ms as not containing an S. Again this finding holds up in three similar replications.

Theories of Visual Search

In this section, an attempt will be made to suggest how each of the theories mentioned in the introduction would handle the present data. Problems to be addressed are (1) the continuum of RT/set size slopes, (2) the increase in RT with set size for the GY color discrimination, (3) the asymmetry of curves and angles, (4) the more efficient search for M versus W than for M versus S, and (5) the asymmetry in the M versus S search.

Original feature integration theory. The early version of FIT (Treisman & Gelade, 1980), with its emphasis on parallel versus serial search, would have placed the targets tested here into a dichotomy of those with shallow slopes or low slope ratios and those with steep slopes or high slope ratios. Such a dichotomy might have placed Ys, OTs, and OYs in the parallel-search group (all with slopes of 10 or less). If slope ratios were used to arbitrarily divide the targets, then GY, M in Ss, and E in Ss would have been considered to be searched by a parallel process. Either of these classifications would have neglected potentially useful information in the data.

Newer feature integration theory. The newer versions of FIT (Treisman, 1991; Treisman & Sato, 1990) could produce explanations for each of the special cases above (A. Treisman, personal communication, July 18, 1991). (1) The continuum of RT/set size slopes would be explained by the grouping hypothesis. If groups of characters are searched serially, this would change the slope ratio. (2) The increase in RT with set size for the GY color discrimination could be explained because Treisman (1991) has suggested that if the target differs only quantitatively from distractors, then attention must be narrowed. These colors may each stimulate both green and yellow detectors, but in different amounts. Parallel search is only predicted when there is no overlap of detector stimulation. Thus, this explanation is not based simply on the similarity of target and distractors. (3) The asymmetry of curves and angles could imply that the curve is the standard target, which is more difficult, and the angle is the curve plus a sharp vertex. Another possibility is that the angle is really just a line with more curvature

than the curve. (4) The more efficient search for M versus W than for M versus S might suggest that line endings are not features, even though they have previously been considered to meet the criterion for separable features (Treisman & Gormican, 1988). Or perhaps M versus W is easy because the three line endings of the target face in the opposite direction of the three line endings of the distractors. (5) The asymmetry in the M versus S searches could be attributed to the unique line ending of the S that points in a different direction, which makes it easier to find than the three line endings of the M or E that are all oriented uniformly. Treisman may be correct in the explanations above, but identifying these features must be done post hoc. In fact, it may not be possible to falsify her model if *any* feature may be defined post hoc.

Guided search. (1) Guided search (Cave & Wolfe, 1990) can explain the continuum of RT/set size slopes because the model includes both the effects of target distractor similarity and the effects of noise. Because the parallel stage guides the serial stage, any information from the parallel stage can improve performance, even for more difficult searches. (2) The increase in RT with set size for the GY color discrimination can be explained by guided search because of the poorer signal-to-noise ratio for GY than for RG or RY (Wolfe & Cave, 1990). Thus, targets and distractors are more similar to one another in the GY case than they are in the other color discriminations. (3, 4, and 5) It is more difficult for the guided-search model to explain the asymmetries that we found. In these cases, the signal-to-noise ratio for target:distractor would be the same for whichever character is the target. Thus, unless one wants to postulate featural differences similar to those postulated by Treisman (personal communication, 1991), several of the results (e.g., the curves and angles, the more efficient search for M versus W than for M versus S, and the asymmetry in the M versus S search) are not explained.

Similarity theory. (1) Similarity theory (Duncan & Humphreys, 1989), like guided search, has no difficulty in handling a continuum of RT/set size slopes because it does not assume a dichotomy. (2) Likewise, the increase in RT with set size for the GY color discrimination can be explained because targets and distractors are more similar to one another in the GY case than they are in the other color discriminations. This theory assumes that there will be increasing difficulty with searches as the target and distractors are more similar. (3) Here, as with guided search, the problem arises with explanation of the asymmetries. Obviously, similarity differences are the same whether the curve or the angle is the target. (4) If anything, similarity theory would predict that M versus S would be an easier search than M versus W because M and W are more similar than M and S. (5) As with angle versus curve, the asymmetry in the M versus S search cannot be explained on the basis of similarities.

Do any of these theories explain all of the data? Considering the above comments, it is not clear that any of the current theories of visual search provide a good explanation of all of the present data. The newer version

of FIT, guided search, and similarity theory each accommodate a continuum of RT/set size slopes and provide reasonable explanations for the increase in RT with set size for the GY discrimination. However, they all could be said to have some problems dealing with the present asymmetries and with why M versus W is easier to find than are M versus S or E versus S. Treisman postulates that the asymmetries are due to an extra feature in the easier search or to the standard feature being more difficult. This suggestion is fairly plausible for the angle-curve asymmetry because if curvature is the feature, it is easy to think of the angle as having more curve. This would be consistent with other searches where "more" of the feature is easier to find than "less" (Treisman & Gormican, 1988).

M versus S and M versus W searches were conducted to test whether differences in the number of line endings is a feature. Our data were the opposite of what one would expect from earlier data (Julesz, 1982; Treisman & Gormican, 1988). The only explanation arising from these theories is Treisman's (1991) suggestion of the unique three line endings pointing in the opposite direction for the target. Perhaps that explanation, or the grouping hypothesis, or other local interactions may be responsible for this difference, but it is not clear that any of these theories could have predicted these results.

Furthermore, none of these theories provide a clear predictive explanation for the asymmetry between M or E and S. These targets are equally similar to their distractors. Moreover, there are other indications in the data that search for Ms versus Ss may be qualitatively as well as quantitatively different. How could one predict that variability would increase more for target-present trials than for target-absent trials for Ms as targets, but not for Ss? Or that when S is the target, there are 2:1 target-absent to target-present slopes, but when E or M is the target, there is not?

The point of these examples is to suggest that search for different targets in different contexts may require that the component processes of search be assembled and executed in different ways. Perhaps a complete theory of search will have to include a repertoire of search strategies that apply to different situations.

Conclusions

Although search rates suggest that the targets tested here may be drawn from a continuum of the amount of attention needed for a successful search, and some searches look more serial than others, there is another interpretation possible. That interpretation is that differences in search rate may indicate that there are not only quantitative differences, but also qualitative differences in the processes used in the different searches. In fact, one important aspect of our work is that it shows how different criteria for parallel or serial search can drastically affect the ordering of tasks along a parallel-serial continuum. In addition, we also demonstrate how other dimensions of search (exhaustive/self-terminating, capacity, etc.) can

be combined with information about serial versus parallel search.

The conclusions in this paper add to the growing body of criticisms of various aspects of present search theories (Bravo & Blake, 1990; Briand & Klein, 1989; Green, 1991; Townsend & Ashby, 1983). These criticisms include, for example, (1) the need to define a priori what constitutes a feature, (2) the need for a dependent measure that reflects spatial attention while minimizing the influence of stimulus characteristics, such as interitem spacing, and (3) the need to consider other measures besides search rate. The analyses presented above indicate that none of the current theories of visual search are completely adequate. Using multiple dependent measures in future work may lead to new theories or more successful revisions of the present theories.

REFERENCES

- BACON, W. F., & EGETH, H. E. (1991). Local processes in preattentive feature detection. *Journal of Experimental Psychology: Human Perception & Performance*, 17, 77-90.
- BECK, J. (1966). Effect of orientation and of shape similarity on perceptual grouping. *Perception & Psychophysics*, 1, 300-302.
- BECK, J. (1982). Textural segmentation. In J. Beck (Ed.), *Organization and representation in perception* (pp. 285-317). Hillsdale, NJ: Erlbaum.
- BECK, J., & AMBLER, B. (1972). Discriminability of differences in line slope and in line arrangement as a function of mask delay. *Perception & Psychophysics*, 12, 33-38.
- BRAVO, M., & BLAKE, R. (1990). Preattentive vision and perceptual groups. *Perception*, 19, 515-522.
- BRIAND, K. A., & KLEIN, R. M. (1989). Has feature integration theory come unglued? A reply to Tsai. *Journal of Experimental Psychology: Human Perception & Performance*, 15, 401-406.
- CARTER, R. C. (1982). Visual search with color. *Journal of Experimental Psychology: Human Perception & Performance*, 8, 127-136.
- CAVANAGH, P., ARGUIN, M., & TREISMAN, A. (1990). Effect of surface medium on visual search for orientation and size features. *Journal of Experimental Psychology: Human Perception & Performance*, 16, 479-491.
- CAVE, K. R., & WOLFE, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology*, 22, 225-271.
- DUNCAN, J., & HUMPHREYS, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433-458.
- EGETH, H., & DAGENBACH, D. (1991). Parallel versus serial processing in visual search: Further evidence from subadditive effects of visual quality. *Journal of Experimental Psychology: Human Perception & Performance*, 17, 551-560.
- FARMER, E. W., & TAYLOR, R. M. (1980). Visual search through color displays: Effects of target-background similarity and background uniformity. *Perception & Psychophysics*, 27, 267-272.
- GREEN, M. (1991). Visual search, visual streams, and visual architectures. *Perception & Psychophysics*, 50, 388-403.
- HOFFMAN, J. E. (1979). A two-stage model of visual search. *Perception & Psychophysics*, 25, 319-327.
- JULESZ, B. (1982). The role of terminators in preattentive perception. In D. Albrecht (Ed.), *Recognition of pattern and form* (pp. 33-58). New York: Springer-Verlag.
- MORAGLIA, G., MALONEY, K. P., FEKETE, E. M., & AL-BASI, K. (1989). Visual search along the colour dimension. *Canadian Journal of Psychology*, 43, 1-12.
- NAGY, A. L., & SANCHEZ, R. R. (1990). Critical color differences determined with a visual search task. *Journal of the Optical Society of America A*, 7, 1209-1217.
- NAKAYAMA, K., & SILVERMAN, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature*, 320, 264-265.

- NEISSER, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.
- NEWSOME, W. T., BRITTEN, K. H., & MOVSHON, J. A. (1989). Neuronal correlates of a perceptual decision. *Nature*, **341**, 52-54.
- QUINLAN, P. T., & HUMPHREYS, G. W. (1987). Visual search for targets defined by combinations of color, shape, and size: An examination of the task constraints on feature and conjunction searches. *Perception & Psychophysics*, **41**, 455-472.
- SAGI, D. (1988). The combination of spatial frequency and orientation is effortlessly perceived. *Perception & Psychophysics*, **43**, 601-603.
- SALZMAN, C. D., BRITTEN, K. H., & NEWSOME, W. T. (1990). Cortical microstimulation influences perceptual judgements of motion direction. *Nature*, **346**, 174-177.
- TOWNSEND, J. T. (1971). A note on the identifiability of parallel and serial processes. *Perception & Psychophysics*, **10**, 161-163.
- TOWNSEND, J. T. (1990). Serial vs. parallel processing: Sometimes they look like Tweedledum and Tweedledee but they can (and should) be distinguished. *Psychological Science*, **1**, 46-54.
- TOWNSEND, J. T., & ASHBY, F. G. (1983). *Stochastic modeling of elementary psychological processes*. Cambridge: Cambridge University Press.
- TREISMAN, A. (1982). Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception & Performance*, **8**, 194-214.
- TREISMAN, A. (1986). Features and objects in visual processing. *Scientific American*, **255**, 114B-125.
- TREISMAN, A. (1991). Search, similarity, and integration of features between and within dimensions. *Journal of Experimental Psychology: Human Perception & Performance*, **17**, 652-676.
- TREISMAN, A. M., & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.
- TREISMAN, A., & GORMICAN, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, **95**, 15-48.
- TREISMAN, A., & SATO, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 459-478.
- TREISMAN, A., & SOUTHER, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, **114**, 285-310.
- WARD, R., & MCCLELLAND, J. L. (1989). Conjunctive search for one and two identical targets. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 664-672.
- WOLFE, M. J., & CAVE, K. R. (1990). Deploying visual attention: The guided search model. In A. Blake and T. Troscianko (Eds.), *AI and the eye* (pp. 79-103). New York: Wiley.
- WOLFE, M. J., CAVE, K. R., & FRANZEL, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 419-433.

(Manuscript received July 10, 1991;
revision accepted for publication January 28, 1992.)