

## Visual search in pigeons: Effects of memory set size and display variables

PATRICIA M. BLOUGH

*Brown University, Providence, Rhode Island*

A visual search procedure compared memory and perceptual effects. Pigeons pecked at a target letter in a three-key forced-choice procedure. Experiment 1 varied memory set and display size. Neither had a significant effect on accuracy, and changing memory set from 1 to 2 items did not affect reaction time. However, reaction times grew longer as display size increased from 3 to 9 items ( $p < .005$ ) and memory set size increased from 1 to 4 ( $p < .05$ ). Experiment 2 extended memory set size to 6 and display size to 18. Four experienced subjects showed no significant effects of memory set size on accuracy or reaction time, while reaction time increased ( $p < .005$ ) with increasing display size. Experiment 3 considered effects of distractor redundancy and target-distractor similarity. Mean reaction times for three experienced birds showed persisting display size effects that depended on target-distractor similarity; search was fastest for redundant distractor sets in which the items were relatively dissimilar to the target. Except for the persistence of a display-size effect, these outcomes are consistent with human data.

A large body of data and a variety of theories address the problem of visual search. Because they provide clues to information-processing strategies, these investigations have been important in human cognitive psychology. Yet the ability to search efficiently must have special significance for many nonhuman species, especially those that depend on sight to locate naturally important items embedded in large, complex backgrounds.

In studies of visual search, subjects typically locate, identify, or indicate the presence or absence of a target within a display. Of special importance are two classes of variables, the size and composition of the display and the size of the memory set. Manipulations of these variables help compare the conditions under which the search process appears to be serial with those under which it appears to be parallel. In serial search, the observer processes each display item separately in time; when search is parallel, several items are processed simultaneously. Reaction time (RT) measures are especially suitable in studies that address this issue; for example, in serial processing, RT should grow as the amount of information in a display increases.

Display size, usually defined as the number of items in a display, has clear effects on the speed of visual search. In a review of some of this literature, Teichner and Krebs (1974) concluded that search time increases when display size increases over a wide

range. When display sizes are small, however, the size effect often lessens with practice. Schneider and Shiffrin (1977) noted this effect and also one of target-distractor separability. When targets and distractors were consistently drawn from separate sets, RT increased only slightly with display size. These authors concluded that search is "automatic" under such conditions; that is, the process is parallel and has minimal attention requirements. In a recent discussion, Fisher (1982) noted that evidence for parallel processing is limited to studies in which the largest display size was six.

Display composition also affects the efficiency of visual search. One important variable is the similarity between the target and distractor items. For example, when target and distractors come from different categories, RT is lower and the effect of display size is lessened (Jonides & Gleitman, 1976). In a study that used colors as display items, Farmer and Taylor (1980) showed increasing RTs as the target's color approached that of the distractor set.

The similarity of distractor items to each other is also important. Additional findings from Farmer and Taylor's research showed more rapid search when distractors had similar colors. The extreme case of similarity is redundancy. Search is more efficient when distractor items are redundant than when they are drawn from a heterogeneous set (Estes, 1972). In Estes's experiment, however, the redundant distractor items were more dissimilar to the target than were the items in the heterogeneous set; thus, target-distractor similarity and distractor redundancy were confounded. McIntyre, Fox, and Neale (1970) distinguished between these variables and also concluded that search is usually more efficient when distractors are redundant; however, accuracy decreases

This research was supported by Grant BNS 80-25515 from the National Science Foundation. Karen D. Friedman assisted with portions of the study; Donald S. Blough provided advice in all its phases. The figures were prepared with the aid of a computer program described by Hayes (1981). Send reprint requests to the author at the Department of Psychology, 89 Waterman Street, Brown University, Providence, RI 02912.

as these items become more similar to the target. This conclusion is generally consistent with Farmer and Taylor's RT data, noted above.

Memory set size is another variable used to distinguish between serial and parallel processing strategies. In a classic series of experiments, Sternberg (1960) showed that RT increased as a linear function of memory set size. From these data, he concluded that memory search is a strictly serial process requiring a fixed amount of time for each memory item. In contrast, Neisser and his colleagues (e.g., Neisser, Novick, & Lazar, 1963) showed that, with sufficient practice, subjects can search for 10 items as quickly as they can for 1. Sternberg did not use a search paradigm; this and a number of other procedural differences help to account for these discrepant findings. However, practice effects seem especially important. Schneider and Shiffrin's (1977) more recent research has shown that well-practiced subjects detect up to 4 memory items almost as quickly and as accurately as they do 1. These authors concluded that an automatic process is seen in memory as well as display search when targets and distractors are consistently drawn from separate sets.

Both memory set size and display parameters contribute to the distinction between serial and parallel search. Yet these two classes of variables are operationally as well as intuitively different. For example, it is easier to observe, manipulate, and interpret the strategies used in examining a display than it is to study memory search. Nonetheless, several approaches attribute common functions to display and memory variables. For example, feature analysis models (e.g., Estes, 1972) suggest that both display and memory items activate feature detectors, which have inhibitory interactions with each other. Such interactions slow target identification; thus operations that vary the number of detectors activated affect search efficiency. Teichner and Krebs (1974) also concluded that search speed would diminish with increasing numbers of items in the display or the memory set. Their analysis combined these factors in a measure of overall information load.

A two-stage model described by Hoffman (1979) also considers both display and memory variables. In an initial stage, the observer selects "candidates" by discarding unlikely items through a rapid, parallel process. Unlikely items are those that are dissimilar to potential targets; thus, more items are discarded when there are fewer targets in the memory set as well as when targets and distractors are dissimilar. The second stage involves serial comparison through which the candidates are compared more slowly with items in the memory set. Hoffman's model accounts for effects of display and memory set size and suggests that both effects will be modified by display composition.

Most investigations and models of visual search have been based on human data. However, a report

by D. S. Blough (1979) demonstrated the pigeon's usefulness in laboratory search tasks. Those experiments suggested that, as in humans, RT depended both on display size and composition; that is, search speed decreased with increasing display size when target and distractors were similar to each other and when distractor items were nonredundant. These effects persisted in well-practiced subjects, suggesting that the birds used serial or controlled strategies with reference to display variables. However, when Blough compared memory set values of one and two items, RTs were almost identical. Thus, within this limited range, his data suggested that memory search occurred in parallel.

The following experiments extended previous work by exploring memory and display variables over a relatively wide range. Further, it assessed interactions among these factors by examining them within a single paradigm. Experiments 1 and 2 considered the effect of memory set size over range of display sizes. Experiment 3 considered the relation between display size and composition. All three experiments used both accuracy and RT measures. Pigeons were subjects, since D. S. Blough's work had suggested intriguing similarities to human findings. Although search appears to be natural to pigeons, there are important differences between avian and human visual systems (e.g., P. M. Blough, 1979; Hodos & Karten, 1974). Species similarities in variables affecting search would offer convincing evidence for common fundamental processes.

## EXPERIMENT 1

Condition 1-2 of Experiment 1 compared search speed and accuracy for a memory set size (MS) of one (MS = 1) and two (MS = 2); Condition 1-4 made those comparisons for MS = 1 and MS = 4 conditions. The birds learned to respond to each target separately before several were combined to form the larger MS. This procedure avoided a problem in D. S. Blough's (1979) research, in which practice with a larger memory set could have affected RT on the smaller set subsequently tested.

A problem common to studies that vary MS occurs when scores for all items in the memory set are averaged. Separate items may be associated with different RTs and accuracies (Yonas & Pittenger, 1973). Thus, apparent effects of MS may reflect the contribution of different sources of variability to the dependent measure. The present experiment examined speed and accuracy with respect to a single "key" target, whether used alone or as part of a larger target set.

### Method

**Subjects.** Six White Carneaux pigeons served in Condition 1-2. They had previously participated in a variety of short projects as part of an undergraduate laboratory. None of these tasks included

complex form discrimination. Condition 1-4 used four pigeons from this set. All pigeons were maintained at running weights that approximated 80% of their ad-lib weights. On days when a bird's weight deviated from its running weight by more than 20 g, its session was omitted.

**Apparatus.** The two experimental chambers were 35 × 50 cm Plexiglas cubicles. Three of the four sides were covered with opaque material. The fourth side, which contained the door, was covered by a black curtain during experimental sessions. A wire-mesh screen covered the floor. The chambers were set on separate shelves inside a sound-attenuating box. White noise, delivered through loudspeakers adjacent to each chamber, helped to mask extraneous sounds.

On the front panel of each chamber was an opening, whose center was 24 cm from the floor and equally distant from the sides of the panel. Behind the opening was a video screen, of which a 5 × 8 cm area was used for the stimulus display. Mounted about 1 cm in front of the screen were three glass response keys, 2.6 cm wide and covering the screen from top to bottom. The keys were separated by gaps of less than 1 mm. A second opening, 7 cm square, in the front panel provided access to an electromechanical food tray. This opening was located 2.5 cm from the box's floor, its position was central in the top box, and its center was 6.5 cm from the left side in the bottom box. A dim lamp, mounted on the top center of the panel served as a house light; an opaque shield prevented the illumination from falling directly on the display screen.

Atari 800 computers, interfaced with the chambers through relay circuitry, provided on-line control of all experimental events.

**Procedure.** Following magazine training, the pigeons learned, through autoshaping, to peck at a small black square displayed behind one of the response keys. Each key was correct equally often during autoshaping.

The final task, learned through a series of approximations, required the birds to respond to a target during a display presentation. The display was made up of black letters on a light background. Each letter subtended a visual angle of approximately 2 deg of arc. The letters were selected on the basis of D. S. Blough's (1982) discriminability data, although their dot matrix format differed slightly from Blough's. Each letter had been discriminated from all others with an accuracy of at least 48% correct in Blough's study. A display included a single target and several distractors. The target was drawn from the memory set; distractors were drawn at random from a different set of four letters. Table 1 shows the letters used as targets and distractors for each bird.

Display size (DS) was 3, 6, or 9 letters. The items were arranged in groups so that an equal number were centered behind each key. The centers of these groups were 2.5 cm apart. When there were two items behind a key (DS=6), they were 1 cm apart, one above the other. For items grouped in threes (DS=9), the third letter had a location halfway between and 0.5 cm to the side of the vertically arranged pair. Thus, the area occupied by the display in-

creased, but at decreasing rate, with DS. In no case were items separated by less than 7 mm, so spatial interference was unlikely (D. S. Blough, 1984).

A session consisted of a series of such display presentations, each preceded by an 1-sec warning signal and followed by a 2-sec intertrial interval (ITI). During the ITI, the display screen was gray. The warning signal was the onset of a bright border around the gray screen. During a display presentation, the screen lightened and the dark letters appeared simultaneously. Only one letter was a target, and a response to the key behind which it appeared was followed by the disappearance of the letters and, with a certain probability, the occurrence of food reinforcement. The ITI followed. Reinforcement probability was 0.1 for all subjects except Bird 553, for whom the probability was 0.07. Duration of reinforcement was 2 to 3 sec; its value was adjusted individually so that each pigeon maintained a constant weight. When responses were correct and no food was scheduled, the screen remained lighted for 1 sec and the ITI followed. Correct responses with reaction times of 0.1 sec or less were exceptions; they were followed immediately by the ITI, although they led to a new trial and were included in the data analysis. Following an incorrect response, the screen immediately turned gray and 4 sec were added to the ITI. The trial was then repeated until a correct response occurred.

Each session began with a series of warm-up trials, during which the target appeared behind each key equally often, but no distractors appeared. There were six warm-up trials for each item in the memory set; randomization and reinforcement contingencies were the same as in the remainder of the session. The session proper consisted of 630 (Birds 284 and 957) or 900 (the remaining subjects) trials, using the displays described above. Except for correction trials, the correct key and the DS were chosen according to a random block design. A single block consisted of 9 trials; during a block, every DS was paired with every target-key combination an equal number of times. A random procedure determined the position of the target within the display behind the correct key. For MS values greater than one, an independent random block procedure selected the target; this block was made up of 6 trials when MS was 2 and of 4 trials when MS was 4.

Memory set size and composition changed over phases, each made up of several series of sessions. Condition 1-2 compared MS values of 1 and 2. At the start of this condition, the pigeons were exposed to series of sessions with the first letter as the target (Table 1). This procedure continued until the bird met a stability criterion, defined as four successive sessions in which there was no consistent upward or downward trend in percent correct or RT. In the next phase, the bird was exposed to a similar procedure with the second letter in the set. After meeting the above criterion, four additional sessions with the second letter provided final data for MS = 1. Testing for MS = 2 then began. The targets were those just learned previously, and the stability criterion was also the absence of trend over four successive sessions. In this, as in other

Table 1  
Procedural Details for Experiments 1 and 2

Experiment 1		Experiment 2								
Bird	Box	Targets*		Distractors	Trials/ Session	Targets				
		1st Condition	2nd Condition			MS = 6	MS = 1**	MS = 4	MS = 2	Distractors
284	Bottom	K,J		T,M,H,L	630	B,J,K,Q,S,Z	K	B,K,Q,S	K,S	C,E,H,I,L,M,T,U
291	Top	A,Y,U,D	L,H	C,Q,E,Z	900	A,Y,D,L,H,U	D	D,L,U,Y	D,L	C,E,J,M,Q,S,T,Z
317	Top	A,Y	U,D,L,H	C,Q,E,Z	630					
328	Bottom	A,Y,U,H	D,L	C,Q,E,Z	630	A,D,L,H,U,Y	D	A,D,H,Y	D,Z	C,E,J,M,Q,S,T,Z
553	Bottom	A,Y,U,D	L,H	C,Q,E,Z	900					
957	Top	K,J		T,M,H,L	630	B,J,K,Q,S,Z	J	J,K,Q,S	J,K	C,E,H,I,L,M,T,U

\*Last letter of a set is the key letter. \*\*Key letter.

multiple-target phases, the criterion was applied to all target letters. Four postcriterion sessions provided the final data for this phase.

Condition 1-4 compared performance for MS=1 with that for MS=4. The targets, but not the distractors, were different from those used in Condition 1-2. The birds learned to discriminate the first three targets singly until the criterion for trend for each was met. Training on the fourth item continued for four sessions beyond criterion to provide data for the reference MS=1 phase. The birds then were tested with a 4-item MS, made up of the four most recently learned targets. Again, four postcriterion sessions provided the final data for this phase. As shown in Table 1, Conditions 1-2 and 1-4 occurred in different orders for different subjects.

## Results

Accuracy and RT measures were computed for each session. Accuracy was expressed as percent correct for each DS and each target item. Reaction time was the time between the onset of the letter display and the response; RT data for single sessions were medians, based on correct responses only, for each target and DS. Both speed and accuracy measures excluded data from the repeated trials that followed errors. Unless otherwise noted, the analyses used means computed over the four postcriterion sessions. Comparisons between MS values were based on speed and accuracy for a single "key" target, the letter that was common to the two conditions. The data were evaluated by analyses of variance for repeated measures on both factors. Outcomes pertaining to MS are described on the basis of two-tailed tests, since practice and MS could have opposite effects. Outcomes pertaining to DS are described on the basis of one-tailed tests, since a large body of data shows an increasing relation.

Figure 1 summarizes the findings in both parts of this experiment. The top panels show accuracy scores as a function of DS. The left side compares these functions for MS values of 1 and 2; the right side makes the comparisons between MS values of 1 and

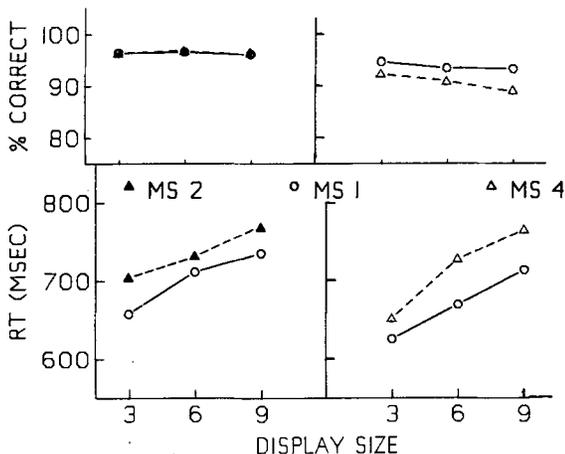


Figure 1. Percent correct and reaction time (RT) for the "key" target as a function of display size for two memory set size (MS) comparisons.

4. Analyses of variance revealed no significant effects on accuracy either of DS or MS in either Condition 1-2 or Condition 1-4. Furthermore, there were no significant interaction effects on accuracy data.

The bottom panels of Figure 1 show RT as a function of DS. As is evident, the effect of DS was significant [Condition 1-2,  $F(2,10) = 19.3$ ,  $p < .005$ ; Condition 1-4,  $F(2,6) = 12.8$ ,  $p < .005$ ]. There was no significant effect of MS in Condition 1-2 despite the consistent disparity between the two functions. While RT increased with MS for four birds, it decreased for the other two. Memory set size did have a significant effect in Condition 1-4, however [ $F(1,3) = 15.7$ ,  $p < .05$ ]. All four birds showed the increased RT in the MS=4 phase, although two were those showing the decreasing relation in the MS=1/MS=2 comparison. There were no significant interaction effects in either condition.

The search task was learned quite easily by all birds. However, the exact course is difficult to summarize, since DS values were introduced one at a time in training procedures that varied among subjects. When the final task began, further analysis evaluated practice effects for Birds 291, 317, 328, and 553. To determine whether the effect of DS diminished with training, an analysis of variance used data from the first four of these sessions; that is, the basis was the MS=1 phase, and the data came from those four sessions in which, for the first time, the three DS values were mixed within a single session. Again, there was a significant effect of DS [ $F(2,6) = 38.6$ ,  $p < .005$ ]. However, there was no significant effect of sessions, and there was no significant interaction between sessions and DS. Thus, the DS effect was present early in training and did not appear to lessen with practice.

Additional examination considered changes in the effect of MS with practice. Reaction times were remarkably stable following the introduction of the larger MS phase. In fact, for the key target, birds almost always met the stability criterion for RT in the initial four sessions of the mixed-target phase. In the single exception, five sessions were required for stability. Early in the mixed-target phases, RTs to key targets tended to be lower than those associated with targets learned earlier. While this effect can be attributed to recency or practice, comparisons among target letters may be complicated by discriminability factors, to be described later.

## EXPERIMENT 2

Experiment 1 showed a clear effect of DS on RT and an effect of MS when sizes of 4 and 1 were compared. It is notable, however, that the birds maintained a high level of accuracy in both conditions. Experiment 2 extended MS to a value of 6 and performed a systematic study of this variable through

a 1-to-6-item range. Furthermore, it increased overall load by increasing the DS range and the number of items in the distractor set.

### Method

**Subjects.** Birds 284, 291, 328, and 957 served as subjects. They were selected for their high accuracy levels in Experiment 1. Between Experiments 1 and 2, Birds 284 and 957 learned to discriminate the letter S from a set of eight distractors; they also worked in a MS = 3 condition in which K, J, and S were targets.

**Apparatus.** The apparatus was the same as that used in Experiment 1.

**Procedure.** As in Experiment 1, the pigeons' task was to peck the key behind which a target letter was displayed. The present experiment consisted of four conditions, which varied according to MS. In the first condition, MS had a value of six. In the following conditions, MS was 1, 4, and 2, in that order. Finally, the MS = 6 condition was repeated. The stability criterion and basis of data analysis were the same as those used in Experiment 1.

Table 1 shows the letters used as targets and distractors in this experiment. Note that the size of the distractor set was 8 and that the items did not perfectly overlap with the set used in Experiment 1. Distractor items were selected on the basis of their discriminability from the letters in the target set (D. S. Blough, 1982). The lowest discriminability score between any target and any distractor was 49% correct. Target combinations were selected on the basis of accuracy scores in the initial MS = 6, DS = 18 condition. Across conditions, the average accuracy score for all targets was approximately constant according to those data.

Display size was 3, 9, or 18, and varied within sessions, as before. In the DS = 3 and 9 conditions, the arrangement of the letters was as in Experiment 1. For DS = 18, there were six letters behind each key; they were arranged in alternating one- and two-letter rows, which were separated by 0.5 cm. Items in two-letter rows were separated by 1 cm. Single letters were placed midway between the items below them. As in Experiment 1, the display's area increased with DS, but at a still more rapidly decreasing rate. Again, the target was randomly positioned in the display behind the correct key.

Experimental sessions consisted of a series of trials arranged like those of Experiment 1. For Bird 291, the number of trials per session was always 900. Bird 284 ran in 900-trial sessions during the initial MS = 6 condition. In the following conditions, trials per session were reduced to 630. For Birds 957 and 328, the total number of trials depended on MS. When MS was 6, there were 900 trials; for smaller MS values, the number of trials was reduced in order to keep the number of presentations of the key target constant. Thus, for MS = 1, 2, and 4 conditions, the number of trials per session was 150, 300, and 600, respectively.

### Results and Discussion

Figure 2 summarizes DS and MS effects, based on means over the four postcriterion sessions. Accuracy was fairly high under all conditions of the experiment; in no condition did any subject's accuracy fall below 83% correct. The shapes of these functions differed between birds, however. Bird 284 maintained very high accuracies in all conditions; Bird 291's accuracy fell with increasing MS, and the other two subjects showed U-shaped functions. The top panel of Figure 2 summarizes the accuracy data. An analysis of variance, with repeated measures on both factors, evaluated the findings by one-tailed tests. It revealed a significant effect of DS [ $F(2,6) = 12.9$ ,  $p < .005$ ]. The source of this effect, not obvious in Figure 2, was an elevated accuracy score at DS = 9; the

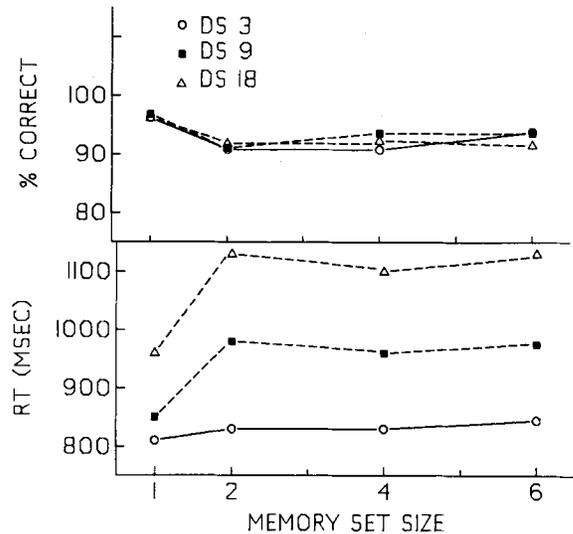


Figure 2. Percent correct and reaction time (RT) for the "key" target as a function of memory set size for three display size (DS) values.

increase was small, but fairly consistent across birds and MS values. The effect of MS was not significant.

The bottom panel of Figure 2 summarizes the RT data. Compared with Experiment 1, overall RTs were elevated. This increase is attributable to Bird 284's unusually high RTs; this subject contributed relatively less to the means for Condition 1-2 and not at all to the means for Condition 1-4 of Experiment 1.

Reaction time data showed a pronounced DS effect, which was seen in the individual data for all four subjects. Again, however, the effect of MS was different for different birds. Bird 284 showed decreasing RTs as MS increased; Bird 291's RTs increased with increasing MS. The other two subjects showed a peak at MS = 2 and then a slight decline at larger MS values. These birds were the two whose session length was varied so that trials with the key target remained constant over conditions. An analysis of variance, with repeated measures for both factors, evaluated the overall findings by one-tailed tests. It revealed a significant DS effect [ $F(2,6) = 26.7$ ,  $p < .005$ ] and a significant interaction between DS and MS [ $F(6,18) = 3.0$ ,  $p < .05$ ]. The effect of MS alone was not significant, despite the elevation in RT (and slight decline in accuracy) when MS = 1 and MS = 2 are compared. This elevation is attributable to the sizable, but unexplained, effect contributed by Birds 328 and 957.

As in Experiment 1, the above findings refer to the identification of a key target that served in all MS conditions. It is possible that the birds' efficiency in locating that letter improved through the course of the experiment. For example, they may have adopted a serial strategy in which the key target was always the first memory item to be compared with the display. According to this interpretation, the absence

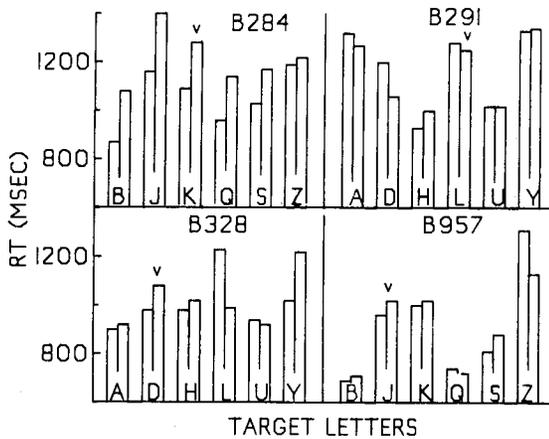


Figure 3. Reaction time (RT) for each memory item in the memory set=6 condition. (The label on each pair of bars describes the memory item; the left bar shows mean RT for the initial series, and the right shows it for replication. The v indicates key letter used for memory set size comparisons.)

of a MS effect would not necessarily indicate parallel processing. Figure 3 addresses this problem. Examination of accuracy, as well as the RTs shown, revealed considerable variability among the six target letters. As planned, key letters were selected so that the associated values fell in the middle of the ranges for the total letter set. If the birds' eventual strategy was to search for the key letter first, the relative RT for that letter should have fallen over the course of the experiment. In fact, however, on replication of the MS=6 condition, those RTs either maintained their positions near the middle of the range or became relatively somewhat longer. Similar comparisons (not shown) at MS values of 2 and 4 revealed that the key letter was in no case associated with the lowest RT. Thus, it is unlikely that the key letter method accounted for the flatness of the RT functions in Figure 2.

The analysis of the MS=6 data also provided correlations between error rate and RT for the separate letters. Based on the initial presentation of this condition, the  $r$  values were .43, .94, .75, and .91 for Birds 284, 291, 328, and 957, respectively. Thus, the birds tended to take longer to locate letters that were less well discriminated, and there was no evidence for a speed-accuracy tradeoff.

### EXPERIMENT 3

Experiment 3 addressed additional questions about the DS variable. Experiments 1 and 2 revealed strong, persistent DS effects. Previous research had shown that the RT-DS relation was less marked when redundant distractor sets were used (Estes, 1972). The redundancy effect seems to be modified by target-distractor similarity, at least when accuracy is the measure (McIntyre et al., 1970). The principal purpose of Experiment 3 was to assess distractor-redun-

dancy and target-distractor similarity effects. Furthermore, it examined the DS variable in greater detail by interpolating additional values. Finally, it indirectly addressed the role of head and/or eye movements in the DS effect. In the previous experiments, increases in display area associated with increasing DS could have contributed to the effect. The present design permitted both display area and DS to vary, but they were not confounded.

### Method

**Subjects and Apparatus.** Birds 291, 328, and 957 participated; they all were subjects in the previous experiments. The apparatus was also the same as that used earlier.

**Procedure.** Throughout this experiment, MS was one and the target was the key letter used in Experiment 2. There were one heterogeneous and four redundant distractor types. The heterogeneous type employed the distractor set of eight letters used in Experiment 2. In the first redundant type, the distractor was a filled, diamond-shaped symbol of the same size as the letters. In the other three, target-distractor similarity was varied on the basis of D. S. Blough's (1982) letter-discrimination data. Table 2 summarizes the stimulus types and notes target-distractor similarity indices as available from D. S. Blough's data. Note that those indices, expressed as percent correct, decrease in value with increasing similarity.

Display size values ranged from 3 to 18 in three-item steps. There were an equal number of items behind each key, and their positions were assigned at random to one of six fixed locations behind that key. Thus, except for the largest DS, there were varying numbers of empty locations, and the items were not necessarily equidistant from each other. However, total area covered by the display was, on the average, the same for all DS types. The position of the target was assigned at random to a location behind the correct key.

All sessions consisted of 900 trials, run in most respects like those in the previous experiments. However, in this experiment, an independent random block procedure determined which key would be correct; there were 6 trials, 2 per key, in each block. A separate random block procedure determined the DS/distractor-type combination. A block consisted of 30 trials made up of all combinations of the display size and composition values.

The stability criterion was the same as that used in the previous experiments. However, the bases of data evaluation were means over seven sessions following the four that met that criterion.

### Results and Discussion

Again, accuracy was high and did not appear to vary with DS. To compare accuracy over distractor conditions, percent correct scores were averaged over DS and appear in Table 2. Although these means show a slight but consistent drop in accuracy for the redundant condition in which the distractor was most similar to the target (R4), this effect was not significant; that is, it did not occur at all DS values for any subject.

Figure 4 shows individual birds' RT data as well as the group means. For two of the three subjects, the DS effect persisted. Bird 328's functions tend to be flatter and, in some conditions, have an inverted U shape. Only the function for the most similar target-distractor conditions showed a clear increase with DS. In this condition, for this bird, the letter discrimination was especially difficult according to D. S.

Table 2  
Distractor Conditions and Percent Correct in Each in Experiment 3

Bird	Target	Redundant												Heterogeneous		
		R1			R2			R3			R4			H		
		DL*	A <sub>1</sub> **	A <sub>2</sub> †	DL	A <sub>1</sub>	A <sub>2</sub>	DL	A <sub>1</sub>	A <sub>2</sub>	DL	A <sub>1</sub>	A <sub>2</sub>	DL	A <sub>1</sub>	A <sub>2</sub>
291	L	♦		97.2	Q	82	97.5	C	68	97.3	T	57	95.5	CEJM QSTZ	71	96.0
328	D	♦		98.9	Z	88	98.0	C	74	99.1	Q	49	95.9	CEJM QSTZ	77	97.1
957	J	♦		91.2	E	84	91.6	T	73	90.8	I	59	89.6	CEHI LMTU	75	91.1
Mean				95.8			95.7			95.7			93.7			94.7

\*Distractor letter(s). \*\*Percent correct (D. S. Blough, 1982). †Percent correct (present Experiment 3).

Blough's data (Table 2). When averaged over all three subjects, the data are quite well described by linear functions.

The heterogeneous distractor condition provides a basis for comparison with Experiment 2, in which DS was slightly confounded with overall field of view. For two birds, the DS effect was similar in magnitude to the comparable (MS=1) condition in Experiment 2. In the case of Bird 291, the RT differences between DS values of 3 and 18 were identical; for Bird 957, the difference was 160 msec in Experiment 2 and 120 msec in the present experiment. Equating field of view should control for head and eye movements. For two of the birds, then, it does not appear that such movements were important deter-

minants of the DS effect seen earlier. One consequence of this control, however, is that the number of potential display locations became the same in all DS conditions. Possibly, Bird 328's RTs reflected time spent scanning empty locations as well as filled ones. Such a strategy would help to account for the peculiar shape of this bird's functions.

Target-distractor similarity had a clear effect on RT. For all subjects, the most similar redundant distractor condition (R4) was associated with higher RTs than the condition in which the distractor was least similar to the target (R1). Data from the intermediate conditions are less orderly; some of this variability may result from individual differences in the ways letters are confused. The functions fit to the averaged data have, both in slope and intercept, an order that corresponds to D. S. Blough's (1982) accuracy findings; that is, the birds searched more slowly as confusability, according to Blough's data, increased. The functions for the seemingly very dissimilar diamond and the least confusable letter nearly overlap; the fact that both increase slightly indicates a persistent effect of DS, even under minimally confusable conditions.

The present findings indicate that distractor redundancy is not always associated with more rapid search. For two birds (291 and 328), when the redundant distractor was relatively similar to the target (R4), search was slower than it was in the heterogeneous condition (H). This effect was especially large for Bird 328, whose uppermost function is based on a particularly confusable letter pair. As noted above, an analogous effect occurred in the accuracy data for all three subjects, since Condition R4 was associated with the lowest accuracy. When similarity was roughly equated, distractor redundancy did have an advantage for Birds 328 and 957. For those subjects, search was slower in almost every instance when distractors were heterogeneous than when they were redundant but similar in discriminability (R3). In the case of Bird 291, however, regression lines fit to the H and R3 distractor types overlapped almost

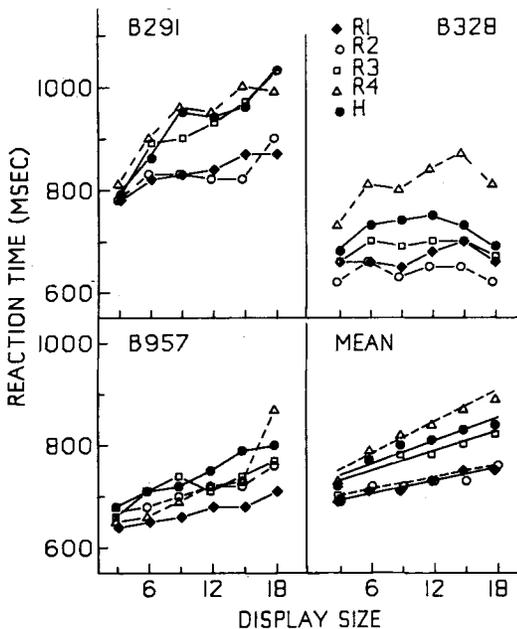


Figure 4. Reaction time (RT) as a function of display size for each of five distractor conditions. (Conditions R1 to R4 employed redundant distractors in order of increasing similarity to the target. Condition H used a heterogeneous distractor set. The method of least squares was used to fit straight lines to the averaged data.)

perfectly; thus, redundancy led to neither more nor less rapid search for this subject.

### GENERAL DISCUSSION

Pigeons searched accurately for as many as six letters under a variety of display conditions. Reaction time, rather than accuracy, proved to be the more sensitive measure of display effects. In one sense, the usefulness of RT is not surprising, since the experimental contingencies were designed to provide an accuracy "set." Yet only a few studies (e.g., D. S. Blough, 1979; P. M. Blough & D. S. Blough, 1978) have found RT to be an effective index of stimulus control in pigeons.

While both DS and display composition had clear effects on RT, MS did not. The present study replicated D. S. Blough's (1979) finding that MS values of 1 and 2 are associated with similar RTs. Reaction time did increase when MS changed from 1 to 4. However, in a subsequent and more extensive manipulation of MS, it no longer had a significant effect. Subject selection probably does not account for inconsistencies between Experiments 1 and 2; all of the subjects in Experiment 2 had shown an increasing relationship between RT and MS in Experiment 1. Birds that worked in Experiment 2 were very well practiced, however. Both Neisser et al. (1963) and Schneider and Shiffrin (1977) noted that the MS effect diminished as a consequence of practice.

Recent research has led to a growing appreciation of birds' memory capacities. Vaughan and Greene (1984), for instance, showed that pigeons can memorize a large number of visual discriminations unlinked by any identifiable concept. In a naturalistic version of a search paradigm, Shettleworth and Krebs (1982) demonstrated that marsh tits recover as many as 12 cached seeds with fair accuracy, despite a large number of empty ("distractor") locations. The present research used RT as well as accuracy measures to elucidate the manner in which the bird processes stored information. In particular, the results of Experiment 2 suggest that well-practiced subjects use, with high accuracy, a parallel strategy for processing up to 6 memory items.

A related study produced disparate findings. Pietrewicz and Kamil (1979) trained blue jays to identify naturally cryptic targets. In within-session comparisons, they found that performance was more accurate for a single-target ( $MS = 1$ ) than for a mixed-target ( $MS = 2$ ) condition. Pietrewicz and Kamil interpreted their findings in terms of foraging strategies: In nature, a particular region is more likely to contain a single prey type than a mixture. Thus, for predators, an efficient strategy is to search for one target at a time. Pigeons may use different foraging strategies, since a patch, natural or unnatural, may contain a variety of foods; therefore, it may be most ef-

ficient to search for several items at once. However, while an ecological interpretation is tempting, practice effects and differences in display composition may better account for the discrepancies between pigeon and blue jay data.

For pigeons, as with humans, all letters are not equally similar to each other (D. S. Blough, 1982). Letter confusability appeared to be important in the experiments reported here. Even well-practiced birds located some targets more quickly than others (Figure 3). It is important to consider such differences in the evaluation of MS effects, especially in studies that average across memory items. Letter confusability also modified the RT-DS relation, which was stronger for more similar target-distractor combinations (Figure 4). These findings are consistent with the human data of McIntyre et al. (1970), in which an accuracy measure was used. That research also included a heterogeneous distractor condition and found, as I did, that the advantage of redundancy is modified by the target-distractor similarity. This finding is not inconsistent with a feature approach (Estes, 1972); certain redundant and heterogeneous distractor sets could be equivalent in shared features with the target.

Recent models of human visual search have preserved the distinction between parallel and serial processing, but have elaborated on the conditions that favor the former. Since the present Experiment 2 used fixed mapping and highly practiced subjects, the absence of a MS effect is consistent with the data of Schneider and Shiffrin (1977). Their model does not account for the persistence of the DS effect, however.

Other approaches stress capacity limitations that are modified by the informational demands of the task (Fisher, 1982; Hoffman, 1979). According to these models, parallel search is favored when displays and memory sets are not too large and when targets and distractors are dissimilar. The results of Experiment 3 are partially consistent with such approaches, since the RT/DS slope was flatter when discriminability improved. However, the data do not define a perceptual capacity within which display search is clearly parallel.

The present data raise intriguing questions about the comparability of memory and display search. Parallel processing of memory items appeared to occur under conditions associated with serial processing of displays (Experiment 2). This finding is inconsistent with the models referred to above; it is also inconsistent with data of Estes (1972), who found a significant MS effect under conditions associated with a marginal DS effect. However, Estes's experiment differed in procedural detail, and it is unlikely that the humans had had practice equivalent to that received by the pigeons described here. In the absence of other comparable human data, it is unclear whether the inconsistencies are peculiar to pigeons. Addi-

tional experiments with humans should explore the relation between memory and display search more extensively. Research with pigeons should seek capacity limits in working memory and conditions in which DS effects diminish still further.

#### REFERENCES

- BLOUGH, D. S. (1979). Effects of the number and form of stimuli on visual search in the pigeon. *Journal of Experimental Psychology: Animal Behavior Processes*, **5**, 211-223.
- BLOUGH, D. S. (1982). Pigeon perception of letters of the alphabet. *Science*, **218**, 397-398.
- BLOUGH, D. S. (1984). Form recognition in pigeons. In H. L. Roitblat, T. G. Bever, & H. S. Terrace (Eds.), *Animal cognition*. New York: Columbia University.
- BLOUGH, P. M. (1979). The functional implications of the pigeon's peculiar retinal structure. In A. M. Granda & J. H. Maxwell (Eds.), *Neural mechanisms of behavior in the pigeon* (pp. 71-88). New York: Plenum Press.
- BLOUGH, P. M., & BLOUGH, D. S. (1978). The reaction-time/luminance relationship for pigeons to lights of different spectral compositions. *Perception & Psychophysics*, **25**, 468-474.
- ESTES, W. K. (1972). Interaction of signal and background variables in visual processing. *Perception & Psychophysics*, **12**, 278-286.
- FARMER, E. W., & TAYLOR, R. W. (1980). Visual search through color displays: Effects of target-background similarity and background uniformity. *Perception & Psychophysics*, **27**, 267-272.
- FISHER, D. L. (1982). Limited-channel models of automatic detection: Capacity and scanning in visual search. *Psychological Review*, **89**, 662-692.
- HAYES, W. (1981). GRAPH: A BASIC-11 graphics program for digital plotters. *Behavioral Research Methods & Instrumentation*, **13**, 367.
- HODOS, W., & KARTEN, H. J. (1974). Visual intensity and pattern discrimination deficits after lesions of the optic lobe in pigeons. *Brain, Behavior, and Evolution*, **9**, 165-194.
- HOFFMAN, J. E. (1979). A two-stage model of visual search. *Perception & Psychophysics*, **25**, 319-327.
- JONIDES, J., & GLEITMAN, H. (1976). The benefit of categorization in visual search: Target location without identification. *Perception & Psychophysics*, **20**, 289-298.
- MCINTYRE, C., FOX, R., & NEALE, J. (1970). Effects of similarity and redundancy on the information processed from brief visual displays. *Perception & Psychophysics*, **7**, 328-332.
- NEISSER, U., NOVICK, R., & LAZAR, R. (1963). Searching for ten targets simultaneously. *Perceptual and Motor Skills*, **17**, 955-961.
- PIETREWICZ, A. T., & KAMIL, A. C. (1979). Search image formation in the blue jay (*Cyanocitta cristata*). *Science*, **22**, 1332-1333.
- SCHNEIDER, W., & SHIFFRIN, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, **84**, 1-66.
- SHETTLEWORTH, S. J., & KREBS, J. R. (1982). How marsh tits find their hoards: The roles of site preference and spatial memory. *Journal of Experimental Psychology: Animal Behavior Processes*, **8**, 354-375.
- STERNBERG, S. (1960). Memory-scanning: Mental processes revealed by reaction-time experiments. *American Scientist*, **57**, 421-457.
- TEICHNER, W. H., & KREBS, M. J. (1974). Visual search for simple targets. *Psychological Review*, **81**, 15-28.
- VAUGHAN, W., JR., & GREENE, S. L. (1984). Pigeon visual memory capacity. *Journal of Experimental Psychology: Animal Behavior Processes*, in press.
- YONAS, A., & PITTINGER, J. (1973). Searching for many targets: An analysis of speed and accuracy. *Perception & Psychophysics*, **13**, 513-516.

(Manuscript received July 5, 1983;  
revision accepted for publication February 28, 1984.)