Converging Evidence for Automatic Perceptual Processing in Visual Search*

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ABSTRACT

Two experiments examined visual search performance both by itself and in conjuction with concurrent, non-visual activity to assess the involvement of attention in the array size effect. Short-term retention was the concurrent activity in Experiment I, and changing S-R mapping during search was the activity in Experiment II. In both experiments, reaction time increased with array size (4, 8, or 12 letters) and concurrent activity, but their effects were additive. The results were interpreted as confirming predictions derived from unlimited-capacity theories of visual search and are related to findings with similar procedures in the memory search paradigm.

The existence of capacity limitations early in visual processing has been a contentious issue in theories of visual search. On the one hand, Rumelhart (1970) and Atkinson, Holmgren, and Juola (1969) have argued that perceptual channels are limited in capacity. Active channels must share processing capacity, and the rate of processing in each channel or in the system as a whole is slower the more channels are activated. Thus, when searching for a particular target in a multi-item array, reaction time increases, and accuracy decreases with the number of active channels (array size). On the other hand, Estes (1972, 1974), Gardner (1973a,b), and Shiffrin and Geisler (1973) argue that no capacity limits exist within perceptual channels. In these models, interactions between channels or confusion among channels converging on a decision process are responsible for the array size effect. Capacity limitations and attentional control affect subsequent stages of processing.

These alternatives have proven hard to distinguish. The strategy guiding research has been to vary the load on the visual system since limited-capacity models are sensitive to load and unlimited-capacity models are not. However, different procedures have favoured different models: manipulation of confusability between target and non-target items (Estes, 1972; Gardner, 1973a) and of presentation rate when arrays are presented item by item (Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972; Shiffrin, Gardner, & Allmeyer, 1973) have tended to support unlimited-capacity models. By contrast, studies manipulating selective cues which indicate the target's position (Beck & Ambler, 1973; Holmgren, 1974; Logan, 1975) support limited-capacity models (but see Gardner, 1973b).

Two aspects of the research effort so far may have contributed to the difficulty of distinguishing the alternatives. The first is the tendency to explore novel situations, e.g., item by item presentation, where performance is only explainable in terms of the favoured alternative. Often the disfavoured model may be modified to accommodate the new findings, and the distinction disappears (Taylor, 1976; Townsend, 1974). Perhaps a better strategy would be to focus on properties well developed in both alternatives (i.e., the explanation of the array size effect).

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A second potential problem lies in the manipulation of visual parameters to vary load. Two separate effects of loading are distinguished in the attention literature. One, identified with attention or central processing capacity, reflects a limited ability to activate separate processing structures concurrently. The other, distinguished from attention, reflects limited coding capabilities of individual processing structures. Thus the performance of any single structure may depend on the extent to which stimulus input approaches the limit on coding capabilities, or the extent to which the supply of central processing capacity meets the demand, or both (Kahneman, 1973; Posner & Snyder, 1975a; Treisman & Davies, 1973). As either or both factors may underlie performance changes associated with manipulations of visual load, the data cannot be interpreted without some ambiguity.

The strategy guiding the present experiments was to manipulate visual load and the load on central processing capacity independently. Visual load was controlled by varying array size, and the load on central processing capacity was varied by engaging the subject in concurrent, non-visual activity. Because such concurrent activity involves non-visual processing structures by definition, it can only influence visual processing if the separate structures share a common source of activation, viz., central processing capacity. Thus, a positive interaction between array size and non-visual load will indicate that capacity factors contribute to the array size effect, whereas a clear case of additivity will indicate a purely structural basis for the effect.

The focus on the array size effect is important theoretically, as it was a major impetus for the development of the alternative models, and distinguishing predictions can be derived easily: limited-capacity models must predict a larger array size effect with a non-visual load than without since the array size effect is itself an index of the load on capacity. Unlimited-capacity models must predict no change in the effect during concurrent activity as only structural factors can affect it.

Two types of concurrent activity were used in the present experiments. In Experiment I, concurrent activity required the use of short-term memory. Subjects performed a two-alternative forced-choice visual search task either alone or in the retention interval of a memory task requiring ordered recall of seven digits. Memory loads of six items or more reliably increase visual reaction time (Logan, 1975; Shulman & Greenberg, 1971; Shulman, Greenberg, & Martin, 1971), and since the tasks require completely separate sets of processing structures, this must be a capacity effect: The attention demands of memory reduce the capacity available for visual processing and this is reflected in longer reaction times. The crucial result in Experiment I is the interaction between memory load and array size.

In Experiment II, concurrent activity involved a change in a non-visual component of the search task while searching. Subjects began each trial with a defined correspondence between target letters and response buttons (hereafter S-R mapping). On concurrent-activity trials, they changed the S-R mapping in response to a signal in the array and pressed the button appropriate to the new mapping. On control trials, an alternate signal indicated that the defined S-R mapping was to be maintained, and subjects pressed the button appropriate to it. Since S-R mapping influences a response selection stage separate from the visual component of the task (Smith, 1968), any effect it has on the array size effect must be attributed to capacity factors. Moreover, the concurrent change in S-R mapping was expected to be effortful, and to reduce the capacity available for visual processing (Howard, 1975). Here, the crucial result is the interaction between array size and changing S-R mapping.

These two concurrent activities were chosen because they have been shown to interact with target set size in memory search tasks (see Sternberg [1969], Experiment 5 for memory load effects, and Howard [1975], for the effects of changing S-R mapping). As memory search is formally similar to the visual search task used here, these findings were taken as evidence that interactions with array size were at least *possible*.

METHOD

Subjects

Eight students from McGill University, four male and four female, served as subjects in Experiment I. Eight students from the University of Waterloo, one male and seven female, served as subjects in Experiment II. Each subject reported normal or corrected vision, and each was paid for participating in one one-hour session.

Apparatus and Stimuli

The visual stimuli in both experiments were arrays containing 4, 8, or 12 different letters equally spaced around an imaginary circle centred on the fixation point. Every array contained one target letter, an A or a V. Each array size was represented by 48 different arrays in which each target letter appeared in each position equally often. Within sampling limitations, the same was true for each non-target letter (all remaining letters except Q). The arrays were made from black uppercase Letraset (#727) mounted on white cards. The exposure of the array was preceded and followed by a fixation field containing a small black dot in the centre of a white field.

In Experiment II, a plus or a minus sign made using capital I's from the same Letraset was placed in the centre of each array to signal the change or maintenance of the instructed S-R mapping. Plus and minus signs appeared equally often with each target letter in each array position.

Experiment I used a Gerbrands three-field tachistoscope (Model T-3B-1) with a viewing distance of 80 cm. At this distance each letter subtended about 26′ × 26′ of visual angle, and the diameter of the imaginary circle subtended about 4° of visual angle. The luminance of fixation and stimulus fields was approximately 8 ftL.

Experiment II used a Scientific Prototype three-field tachistoscope (Model GB). Since its viewing distance was substantially longer (122 cm), the stimuli appeared smaller. Each letter subtended about 19′ × 19′ of visual angle, and the diameter of the imaginary circle subtended about 2°53′ of visual angle. The luminance of stimulus and fixation fields was approximately 29 ftL.

In both experiments, the arrays were exposed for 1500 msec. The tachistoscope timers were started 500 msec before the array was exposed so that the click of the switch initiating the timing sequence could serve as a warning signal.

Reaction time was measured in msec from the onset of the array, using a digital timer. The timer was started by the tachistoscope timers and stopped when the subject pressed one of two buttons attached to microswitches mounted in a panel in front of him/her. Pressing each button also illuminated a separate light visible to the experimenter so that response accuracy could be monitored.

In Experiment I the memory stimuli were random strings of seven unique digits recorded at a rate of .75 sec per digit and played back through a speaker at a comfortable listening level. A different list was used on each trial. Each list was preceded by a warning signal ('your next list is') and followed by a ready signal ('ready') which occurred about 1.5 sec after the last digit. A 500 msec dark interval in the tachistoscope occurred 5 sec after the array terminated to signal the beginning of the recall phase. Thus, the retention interval was approximately 8.5 sec. Subjects were allowed as much time as they required for recall, but most subjects completed recall within 15 sec.

Procedure

Experiment I. Trials involving a memory load consisted of the following sequence of events: (1) the presentation of the memory list; (2) the presentation of a verbal ready signal; (3) the subject's affirmative reply to the ready signal indicating that he or she had the fixation point in sharp focus; (4) the exposure of the array; (5) the subject's response to the array; (6) the subject's recall of the memory digits in the order in which they were presented. Trials not involving a memory load omitted events (1) and (6).

Each subject completed 144 trials in four 36-trial blocks. Each array size and target letter appeared equally often in random order in each block. Memory load and no memory load conditions were run alternately in separate blocks. Each subject received the 144 arrays in the same order, but the order of memory load conditions varied between subjects in such a way that half the subjects began with no memory load (i.e., no load, load, no load, load) and half began with a memory load (i.e., load, no load, load, no load).

Half of the subjects pressed one button with the index finger of their right hand to indicate that the array contained an A and the other button with the index finger of their left hand to indicate a V. The correspondence between buttons and targets was reversed for the other half of the subjects, and assignment to these conditions was orthogonal to the order of memory load conditions.

Instructions described the sequence of events on memory load and no memory load trials, and examples of visual and memory stimuli were given. Specifically, subjects were instructed to respond to the visual task as quickly as possible without making errors, and to concentrate on the memory task during memory load trials so as to optimize performance on it. Thus according to instructions, the memory task was the more important of the two.

Prior to testing, each subject received 20 practice trials with single A's and V's presented 2° above the fixation point. Subjects were not given feedback in practice or in the experiment.

Experiment II. The sequence of events on each trial was the same as that for no memory load trials in Experiment I.

Again, each subject completed 144 trials in four 36-trial blocks. Each array size, target letter, and signal (plus or minus sign) appeared equally often in random order in each block and each subject received the 144 trials in the same order.

Instructions decribed events in the visual task complete with examples, and stressed both speed and accuracy in responding. In the initial description of the visual task, only one S-R mapping was described. Half of the subjects were told to press with their right hand for A and their left hand for V, while the other half were told the opposite. Later, they were told to maintain this mapping between trials and in response to a 'same' signal in the centre of the array. If a 'change' signal appeared, they were to reverse the instructed S-R mapping (i.e., if instructed to press right for A they would now press left). For half of the subjects the plus sign signalled 'same' and the minus sign signalled 'change' while for the other half, plus signalled 'change' and minus signalled 'same.' Assignment to these conditions was orthogonal to the initial S-R mapping. Maintenance of the initial S-R mapping was emphasized; subjects were told to reverse the initial S-R mapping only in response to a 'change' signal and then to prepare the initial mapping again for the next trial.

Altogether, each subject received 72 practice trials with single A's and V's 1°26′ above fixation. No plus or minus signs appeared on the first 24 arrays and subjects first practised the initial S-R mapping. For the next 48 trials, a plus or minus sign appeared in the centre of the array, and subjects practised maintaining and changing S-R mapping in response to the signals. Feedback about speed and accuracy was given during practice but not during the experiment itself.

RESULTS

In both experiments, each subject completed 24 trials under each combination of experimental conditions. Mean reaction times were computed for each subject for correct responses in each condition. Reaction times exceeding 2900 msec were scored as errors to reduce skew in individual reaction time distributions. The mean reaction times across subjects in each experiment are shown in Figure 1. Each point in the figure is based on 192 observations. Error rates and the slopes and intercepts of the best-fitting linear functions relating reaction time to array size are shown in Table 1.

Experiment I

The results can be summarized as follows: Reaction time increased with array size and with memory load, but the magnitude of the array size effect was not different in the two memory load conditions.

This pattern of results is supported by analysis of variance. The main effects of array size and memory load were significant, $F(2,14) = 119.87$ and $F(1,7) = 14.42$, respectively, $p < .01$, but the interaction between them was not, $F(2,14) < 1$. The same conclusions can be reached (though not independently) by examining the slopes and intercepts of the reaction time by array size functions in Table 1. Adding a memory load *reduced* the slope by 4 msec, but increased the intercept by 118 msec. Correlated t-tests indicated that the former difference was not significant, $t(7) < 1$, while the latter was $t(7) = 3.51$, $p < .01$.

It is possible that subjects maintained a constant rate of visual search by trading recall accuracy for speed in the visual task. Thus, it is important to consider recall accuracy as a function of array size. Accordingly, the number of digits recalled in cor-

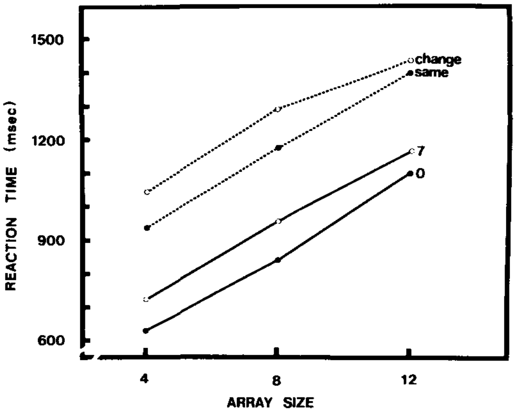

FIGURE I Mean reaction times in Experiment I (solid lines) and Experiment II (dotted lines) as a function of array size (control and concurrent activity conditions are parameters: control = filled circles; concurrent activity = open circles).

rect order at each array size was computed for each subject. The means across subjects were 6.20, 6.02, and 6.18 for four-, eight-, and 12-letter arrays, respectively (maximum = 7). As analysis of variance indicated that array size had no significant effect on recall accuracy, $F(2,14) = 1.76$, $p > .05$, there is no support for a trade-off strategy between tasks, and the conclusion that memory load and array size have additive effects on reaction time appears warranted.

Experiment II

The results can be summarized as follows: Reaction time increased with array size, and with the requirement to change the S-R mapping during search. However, the change attributable to changing S-R mapping had no reliable effect on the magnitude of the array size effect.

Again, this pattern of results was supported by analysis of variance. The main effects of array size and changing S-R mapping were significant, $F(2,14) = 55.47$, $p < .01$ and $F(1,7) = 10.37$, $p < .05$, respectively, but the interaction between them was not, $F(2,14) = 3.06$, $.05 < p < .10$. The slope of the array size function was *reduced* by 10 msec when the S-R mapping was changed during visual search, but the intercept increased by 166 msec. The former difference was not significant by a correlated t-test, $t(7) = 1.78$, $p > .05$, while the latter was, $t(7) = 5.42$, $p < .01$. Thus the conclusion that changing the S-R mapping did not *increase* the magnitude of the array size effect appears warranted.

TABLE I

Slopes and intercepts (in msec) of the best-fitting linear functions, and proportion of errors as a function of array size in each condition in each experiment

Experiment	Condition	Slope	Intercept	Array size 4	8	12
I	0	59	388	.04	.03	.01
	7	55	506	.03	.03	.06
II	Same	59	702	.03	.05	.13
	Change	49	868	.15	.13	.21

Experiments I and II

In order that the conclusions drawn from the separate experiments may converge on the theories at issue, it is useful to compare performance in the conditions without concurrent activity, namely the no memory load condition from Experiment I and the 'same' condition from Experiment II. These conditions were supposed to approximate 'standard' search conditions, and although the no memory load condition was procedurally identical with standard search, the 'same' condition must require additional processes to deal with the signal. Possibly, these additional processes may have altered the behaviour of the structures underlying the array size effect. The slope estimates in Table I provide the relevant data, and the numerical identity of the estimates from the two tasks suggests that the same visual structure was used in both experiments.

However, the intercept of the 'same' function was 314 msec larger than the 'no memory load' intercept, indicating that Experiment II involved some additional processes. This difference is similar to the 257 msec difference between Sternberg's

TABLE II

Mean reaction times and proportions of errors in standard, same and change conditions of practice in Experiment II

Measure	Standard	Same	Change
Reaction time	393	661	715
Proportion errors	.05	.12	.17

(1969, Experiment 5) 'no memory load' intercept and Howard's (1975) 'same' intercept in memory search.

The practice data from Experiment II are presented in Table II to provide a further comparison. The data from the first 24 trials approximate standard search conditions, as the S-R mapping instruction was not in effect and no signals were presented with the targets. Mean reaction time here was 268 msec faster than the mean 'same' reaction time, and the difference was significant by a correlated t-test, $t(7) = 11.94$, $p < .01$. Note that the confounding with order should reduce the difference.

Thus, it appears that Experiment II did involve additional processes not required in Experiment I, but these processes did not alter the functioning of the structures underlying the array size effect. As these structures are the focus of theoretical interest, converging conclusions from the two experiments appear warranted.

DISCUSSION

The results of both experiments can be summarized as follows: reaction time increased with array size and with concurrent activity, but their joint effects were additive, that is, the array size effect was not larger with concurrent activity than without. In terms of the alternatives outlined in the Introduction, this suggests that central processing capacity is *not* involved in the perceptual processing that underlies the array size effect. Limited-capacity models predicted a larger array size effect when attention was distracted by concurrent activity, but this did not occur. Rather, the invariance of the array size effect under different conditions of attention is consistent with unlimited-capacity models.

These results present an interesting contrast with related findings in the memory search paradigm. In memory search, the requirement to retain seven items up to the exposure of the array (Sternberg, 1969, Experiment 5) or to change the S-R mapping during search (Howard, 1975) *increases* the slope of the function relating reaction time to target set size in a manner consistent with the idea that search requires capacity. The simplest explanation is that the process comparing the array with the target set is different in the two types of search (Townsend & Roos, 1973), requiring capacity in memory search but not in visual search.

However, it is possible that the same process is involved in both paradigms. Array size and target set size may be different parameters converging on a common process, and indeed, this is supported by the strong interactions found between them when they are varied together in the same experiment (Briggs & Johnsen, 1973; Johnsen & Briggs, 1973; Nickerson, 1966; Sternberg, 1967). The process itself might simply involve automatic summation of activation in units (i.e., feature detectors) representing items common to the array and the target set. When the activation reaches some criterion value, a response can be emitted. Response latency, then, will depend on the time required for activation to sum to the criterion. If the criterion represents a constant signal-to-noise ratio, response latency will be sensitive to array size and target set size, as the irrelevant items in the array and the target set will determine the noise level (cf., Anderson, 1973). Thus, larger arrays and target sets will yield smaller signal-to-noise ratios, and more time will be required to sum to the criterion.

The important consideration with respect to capacity is the *source* of activation for the array and target set items. Presumably, units representing the array are activated automatically by stimulus presentation. This is consistent with the present findings. Units representing the target set, however, cannot be activated by stimulus presentation since the target set is usually presented several seconds – and sometime minutes or hours – before the array. Thus, the source of activation for the target set must be internal, and it is possible that central processing capacity provides the necessary activation (cf., Baddeley & Ecob, 1973). Indeed, there is evidence from letter-matching tasks that capacity is used to prepare the target for comparison (Comstock, 1973, 1975; Millar, 1975; Posner & Boies, 1971; Posner & Klein, 1973; Posner & Snyder, 1975b; also, see Corballis, 1975).

Given the different sources of activation for the target set and array, the different capacity requirements of visual and memory search are easily reconciled: the activation of the target set requires capacity, but the activation of the array does not. Thus, the target set will contribute to the capacity requirements of the task but the array will not. In visual search, capacity requirements will be constant for all array sizes as the target set is the same for all arrays. Since summation of activation is an automatic process, the array size effect will not be altered by concurrent activity. In memory search, however, capacity requirements will increase with target set size, so the effect of concurrent activity (presumably on some stage other than comparison) will be greater the larger the target set. Thus the target set size effect should be stronger with concurrent activity than without.

To conclude, the present analysis suggests that perceptual processing is relatively free from on-line attentional control. Attention has its influence by imposing an additional pattern of activity – that representing the target set – on the pattern resulting from stimulation. The abstraction of aspects of perceptual activity relevant to response requirements results from an automatic summation of activation in units common to the target set and the array. Since the active involvement of attention seems to occur before the array is presented, search may be viewed as a special case of the general phenomenon of *mental set* (Haber, 1966), and research might be directed towards those prior processes that make search possible.

RÉSUMÉ

Deux expériences sur l'activité de recherche visuelle (étudiée en elle-même et en relation avec une activité concurrente non visuelle) afin d'évaluer le rôle de l'attention dans l'effet produit par l'étendue du matériel présenté. Dans l'expérience I, c'est la rétention à court terme qui sert d'activité concurrente et, dans l'expérience II, c'est la modification de la relation S-R pendant la recherche visuelle. Les deux expériences montrent une augmentation du temps de réaction avec l'étendue du matériel (4, 8, ou 12 lettres) et avec l'activité concurrente, ces deux effets jouant de façon additive. L'interprétation voit dans ces résultats une confirmation des prédictions faites à partir des théories préconisant une capacité illimitée de recherche visuelle et confronte ces résultats avec les données recueillies par des techniques analogues utilisées dans les études sur la recherche mémorielle.

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