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Visual search has memory: Evidence from multiple target search

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Recent studies have proposed two opposing models regarding the function of memory in inefficient visual search, a memory-driven model and a memory-free model. Horowitz and Wolfe (2001) examined the reaction time x n function in a multiple target search task: Participants were required to respond whether there were at least n targets present in the display or not. They demonstrate the positive and accelerated curve of the reaction time x n function, suggesting that no record is kept on the deployment of attention during inefficient search (i.e., the memory-free model). The conclusion in their study is based on the assumption that the n is irrelevant to search rate, although the mental load is heavier when participants look for a large number of targets. In the present study, I varied the total set size, and fitted the models separately for each n condition. The model fitting resulted that the memory-driven model is more appropriate than the memory-free model. The results indicate that the positive and accelerated curve of the reaction time x n function is the result of increasing search rate with increasing n and not due to an amnesic process.

Keywords: visual search, serial process, memory, inhibition of return, multiple target search

Introduction

There are two opposing models regarding the function of memory in the serial deployment of attention in inefficient visual search: a memory-driven model and a memory-free model. The memory-driven model proposed that previously attended distractors are memorized and inhibited to prevent the ineffective reexamination of rejected distractors in inefficient search (see Klein, 2000 for review). On the other hand, the memory-free model assumed that no record is kept on the serial deployment of attention during a search, suggesting that previously attended and rejected distractors could be reexamined (e.g., Horowitz & Wolfe, 1998).

In the previous studies, this issue has been examined by using three methods. These are by (a) using reaction times (RTs) for detecting probes after visual search (Klein, 1988; Müller & von Mühlenen, 2000; Ogawa, Takeda, & Yagi, 2002; Takeda & Yagi, 2000); (b) using the monitoring refixation of eye movements during visual search (Peterson, Kramer, Wang, Irwin, & McCarley, 2001; Gilchrist & Harvey, 2000); and (c) using the RT x set size function in a dynamic display (search items were randomly relocated, Horowitz & Wolfe, 1998, in press; Kristjansson, 2000). The previous studies using the method (a) have demonstrated increased RTs for detecting probes on the previously attended distractors, suggesting that these distractors are memorized and inhibited. Although the results support the memory-driven model, it has been pointed out that detecting probes is not a direct measure of the serial deployment of attention during visual search (Horowitz & Wolfe, 2001). On the other hand, studies using the methods (b) and (c) have demonstrated inconsistent findings: some studies provided the evidence for the memory-driven model, but the others supported the memory-free model.

Recently, Horowitz and Wolfe (2001) have proposed a new method of examining the nature of memory in visual search. In their study, observers were required to decide whether or not at least n targets were present in the display. They held total set size, varied the number of search targets (n) and the number of actual targets in the display (t). RT in the memory-driven model can be predicted by the following equation.

$$RT = b + \frac{nr(t + d + 1)}{t + 1}$$

Parameters (b), (r), and (d) indicate an intercept, a search rate (i.e., time for examining each item), and the number of distractors in the display respectively. RT in the memory-free model can be predicted by the following equation.

$$RT = b + \sum_{i=1}^{n}\left[1 + \left(\frac{d + i - 1}{t - i + 1}\right)\right]r$$

The equations indicate that the memory-free model predicts a positive and accelerated curve of the RT x n function in each t, whereas the memory-driven model predicts a linear function. Horowitz and Wolfe (2001) demonstrated that the RT x n function is positive and accelerating.

Although the results from the multiple target search task support the memory-free model, this evidence is controversial. The model is based on the assumption that n is irrelevant to r, although the mental load is heavier when participants look for a large number of targets (see Tuholski, Engle, & Baylis, 2001). Recent studies have demonstrated that the spatial working memory load and executive process during search increase search time (Han & Kim, 2002; Oh & Kim, 2002, but see also Woodman, Vogel, & Luck, 2001). This suggests that r may increase with increasing n. if so, the RT x n function would accelerate positively, even if reexamination of reject distractors did not occur.

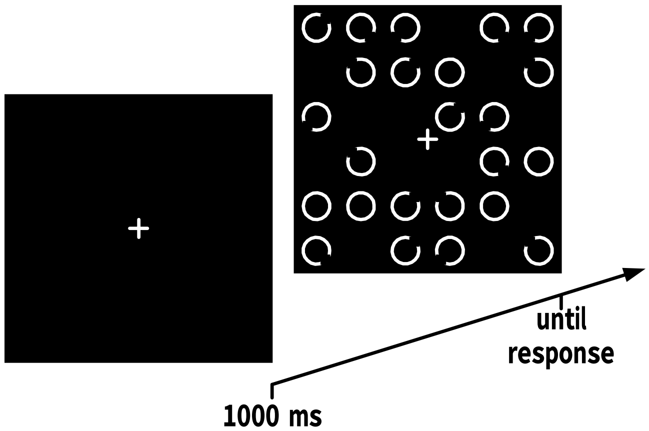

Figure 1. An example of array of stimuli used in the present study.

In the present study, I varied total set size (*t*+*d*) and *t*, and examined RT functions for the interaction between (*t*+*d*) and *t* when *n* was constant. The memory-driven model predicts different RT function from the memory-free model, even when *n* is constant. Therefore, the present study was designed to isolate the confounding effects of mental work load and clarify the function of memory in visual search.

Method

Participants

Forty-two paid volunteers (10 males and 32 females, aged 18–27, *M*=21.2 years) participated in the present study. All had normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were presented on a 17-inch color monitor (IIYAMA A702H, with 1280 x 1024 resolution) controlled by an IBM PC-AT compatible computer (DELL Precision 620).

Each trial began with the presentation of a white fixation cross at the center of the display (see Figure 1). One second after the onset of the fixation, search stimulus appeared at randomly selected locations of an invisible 6 x 6 matrix, which subtended a visual angle of 6° x 6°. The search stimulus consisted of white circles (targets) and white arcs (distractors). The diameters of these items subtended 0.6° of visual angle. Set sizes of 12, 18, and 24 were used with equal probability. The fixation and the search stimulus were presented until the participants responded. All stimuli were displayed on a dark background in a semi-dark room.

Design and Procedure

For the number of search targets (*n*), there are three conditions; a one-target search condition (*n*=1), a three-target search condition (*n*=3), and a five-target search condition (*n*=5). Each condition was performed in three groups (14 participants for each condition). Participants were required to respond whether or not at least *n* targets were present in the display by pressing one of two keys with their right or left index finger as quickly as possible. In half of trials, *n*-1 targets were presented (i.e., negative trials). In the remaining trials, *n*, *n*+1, *n*+2, *n*+3, or *n*+4 targets were presented with equal probability (i.e., positive trials). Experimental session consisted of 1080 trials. Short breaks were given after every 60 trials. Each participant practiced for 60 trials before the experimental session.

Results and Discussion

RT x *n* function

One participant in the five-target search condition was excluded from the analysis, because she misunderstood the task. The mean correct RTs and mean error rates in the positive trials as a function of *n* are shown in Figure 2. Similar to Horowitz & Wolfe’s study, the curves of the RT x n function are positively accelerated in each set size when five actual targets were presented. The RTs in the five actual target condition were subjected to a quadratic trend analysis separately for each set size. In all set sizes, the significant quadratic trends were observed, F (1, 38)= 13.8, $p< .001$ in set size 12, F (1, 38)= 9.0, $p< .005$ in set size 18, F (1, 38)= 6.8, $p< .05$ in set size 24. Although the results of the RT x *n* functions are consistent with the findings from Horowitz & Wolfe’s study, as I have mentioned in the Introduction, the accelerated curves may be due to the result of increased r with increasing *n*. A model fitting analysis can examine this possibility.

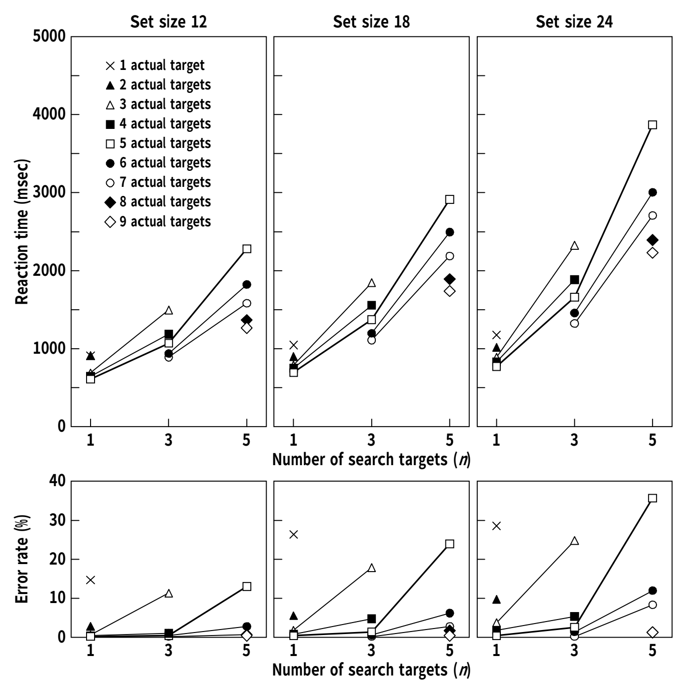

Figure 2. Mean correct reaction times and error rates as a function of number of search targets (*n*).

Model fitting

To examine whether attention was controlled by the memory-driven mechanism or by the memory-free mechanism, each model was fitted separately for each *n*, using a least root mean squared (RMS) error criterion. The fifteen data points of mean correct RTs in the positive trials (5 actual target conditions x 3 set sizes) were fitted to the memory-driven and memory-free models. The search rate (*r*), the intercept (*b*), and RMS error, estimated in each model, are shown in Table 1. In all *n* conditions, RMS errors in the memory-driven model were smaller than those in the memory-free model, suggesting that the memory-driven model is a more appropriate explanation of function of memory in visual search than the memory-free model.

Each model was also fitted separately for each participant, and a *t*-test was performed on RMS errors for each *n*. RMS error was significantly smaller in the memory-driven model than in the memory-free model in the one-target search condition (n= 1), t (13)= 7.4, p< .0001, and in the three-target search condition (n= 3), t (13)= 3.6, p< .005, although the *t*-test failed to reach significance in the five-target search condition (n= 5), t (12)= 1.8, p= .10.

As I have mentioned in the Introduction, the spatial working memory load and executive process during search may increase search rate, predicting that the search rate increased with increasing *n*. The results of the model fitting in the memory-driven model in the present study are consistent with this prediction (54.0 ms / item in the one-target search condition, 102.3 ms / item in the three-target search condition, and 167.9 ms / item in the five-target search condition). The search rates estimated on the memory-driven model were subjected to a one-way analysis of variance (ANOVA) with *n* (1, 3, or 5) as the main term. The main effect was significant, F (2, 38)= 26.9, p< .0001. This finding suggests that the positive and accelerated curves of the RT x *n* function are the result of increasing search rate with increasing *n* and not due to the memory-free search.

Table 1 Results of model fitting

	Search rate (ms/item)	Intercept (ms)	Capacity (items)	RMS error (ms)
One-target search (*n*=1)				
MD	54.0	543.6		42.0
MF	24.3	641.3		57.4
LC	53.7	544.4	22	41.9
Three-target search (*n*=3)				
MD	102.3	388.5		33.6
MF	36.2	791.2		104.3
LC	101.2	398.5	21	31.7
Five-target search (*n*=5)				
MD	167.9	189.6		113.2
MF	53.2	1011.6		185.0
LC	156.2	310.8	19	100.4

Note. MD= the memory-driven model; MF= the memory-free model; LC= the limited-capacity model.

Capacity of memory

The pure memory-driven model assumes that the previously attended and rejected items were perfectly memorized and no reexamination of those items occurred. It is considered that the capacity of memory is infinity or at least more than the set size. On the other hand, the pure memory-free model assumes that the previously attended items and the unattended items can be examined with equal probability. This indicates that the capacity of memory is zero. A limited-capacity model allows capacity to vary between zero and infinity (or set size).

Similar to the previous model fitting, the fifteen data points of mean correct RTs in the positive trials were fitted to the limited-capacity model, using a least RMS error criterion. Table 1 shows the search rate, the intercept, the capacity, and RMS error. The estimated capacity was approximately 20 items in each *n*. The results indicate nearly perfect memory in visual search, although the capacity failed to reach set size (i.e., 24 items).

Conclusion

Similar to Horowitz and Wolfe, the results in the present study demonstrated the positive and accelerated curve of the RT x *n* function. However, the results from the model fitting separately for each *n* indicate that a memory-driven or a large capacity (approximately 20 items) mechanism is a more appropriate explanation of function of memory in visual search than the memory-free mechanism. Furthermore, the search rate, estimated on the memory-driven model, increased with increasing *n*, suggesting that the positive and accelerated curves of the RT x *n* function are the result of increasing search rate with increasing *n* and not due to the memory-free search. The results in the present study demonstrate that the previously attended and rejected items are memorized and inhibited to prevent the ineffective reexamination of those items during visual search.

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Appendix

Mean correct RTs (ms) and error rates (%) in the negative trials

	Set size		
	12	16	24
One-target search	1196.4 (0.7)	1454.9 (0.7)	1642.4 (0.8)
Three-target search	1961.7 (4.0)	2480.1 (2.6)	2935.7 (2.5)
Five-target search	2642.8 (4.0)	3524.0 (5.6)	4260.5 (5.0)

Note. Error rates are in parentheses.