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Distinct load effects by set-size and target-distractor similarity in visual search

Suk Won Han†

Department of Psychology, Chungbuk National University
Department of Psychology, Vanderbilt University

Using the simultaneous-sequential presentation search paradigm, we investigated how different types of load manipulation would tap into attentional resources and the concrete mechanism by which search would be performed. Search display perceptual load was manipulated by set-size and target-distractor similarity. The benefit of sequential presentation was larger when the load was increased by number of search items than when target-distractor discrimination was made more demanding. Considering that the load effect could be result from both perceptual load and statistical decision noise, the current results are explained by suggesting that set-size will determine whether the search process will be serial or parallel, regardless of perceptual difficulty. Factors that can set the limit of attentional resources are also discussed.

Key words : visual search, capacity limit, serial process, parallel process

† 교신저자 : 한석원, 충북대학교 심리학과, (362-763) 충북 청주시 서원구 충대로 1
E-mail : suk.w.han@gmail.com

The visual search paradigm has been used extensively to investigate selective attention and the capacity limit in information processing. Numerous studies have shown that increasing perceptual load of search stimuli accompanies behavioral impairment (Duncan, 1980; Lavie, 1995; Lavie, Hirst, DeFockert, & Essi, 2004); when the number of search items is increased, or perceptual discrimination of each item is made more demanding, either accuracy drops or reaction time increases. This "load effect" has been interpreted as the evidence of capacity limit.

However, a number of alternatives should be considered before attributing any kind of load effect as being attentional in nature. First, the load effect observed by increasing set-size might be due to statistical decision error, which is immune to any capacity limit. Assuming that sensory signals of search stimuli are noisy, the probability of confusing one of the non-target items with the target at least once would increase when there are many items regardless of the capacity limit (Huang & Pashler, 2005; Palmer, 1994). On the other hand, when perceptual discrimination is more demanding, it has to be proven that the observed load effect was not due to any sensory factor or inherent limit in the resolution of the visual system (Lavie & DeFockert, 2003). In other words, it has to be distinguished whether the load effect was originated from a limitation in attentional resources or data.

The simultaneous-sequential presentation search paradigm was developed to investigate the attentional capacity limit, avoiding these confounds. Presenting items across multiple frames allows one to concentrate attentional resources on only a subset of stimuli at any instant in order to improve accuracy. Thus, a significant benefit in accuracy by sequential presentation would reflect a capacity limit. However, improved accuracy by sequential presentation would not tell anything about the concrete mechanism of visual search. Specifically, it remains to be clarified whether different types of load manipulation (set-size and perceptual difficulty) would consume a resource in the same way or not. In addition, it is yet to be specified whether a search process would be done in parallel or serial and what determines the way in which the search would be performed.

Numerous studies suggest that humans can activate three or four processing channels (slots) simultaneously (Duncan, 1980; Fisher, 1982; Fisher, Duffy, Young, & Pollatsek, 1988). If the capacity of this processing resource is limited, it is reasonable to hypothesize that serial processing would be required when the set-size exceeds four. A limited resource should be allocated to a subset of stimuli and that resource is disengaged from the first subset and reallocated to the

other stimuli (Duncan & Humphreys, 1989). When perceptual discrimination of each item is more demanding, requiring higher attentional resolution for a single stimulus, there are two possible ways to resolve this situation. On the one hand, as long as the set-size does not exceed four, the search process might still be parallel regardless of perceptual difficulty of search items. Here, the impaired behavioral performance would be due to information overload for each channel, activated concurrently. On the other hand, for more demanding perceptual discriminations, the maximum number of active channels might decrease, thus only one or two items would be processed in parallel, in which case serial processing is necessitated even with a set-size smaller than four.

To gain more insight into answering these questions, the distinction between serial and parallel processing needs to be considered in the context of decision making and statistical decision noise. The main advantage of the simultaneous-sequential presentation is that this method can reveal the capacity limit without being confounded by statistical decision noise. Presenting stimuli sequentially would reduce the perceptual load of the display for a given period of time, but it would not change the total number of noise sources (i.e., the number of items) and the amount of statistical decision noise. However, this assumption holds true only when the search process was done in parallel. In parallel processing, only one decision would be necessary, in which every stimulus should be taken into account in an integrative manner (Palmer, 1994). Consequently, statistical decision noise will remain the same even when items are presented sequentially across multiple frames, and the significant benefit by sequential presentation will reflect only the capacity limit. In serial processing, there should be multiple independent decisions for each subset of stimuli at a given time. For example, if there are eight items, resources might be allocated to only four items at first. These items will be processed in parallel, and a decision about the presence of target can be made. For this first decision, only four items being processed in parallel might be considered to be candidates for the target, and only these items will contribute to the decision. If no target is found in the first subset, resources will be reallocated to the second subset and another decision will be made, based only on the newly attended four items. In this case, sequential presentation will reduce the number of items to be processed at a given time, and also reduce the sources of statistical decision noise.

As described above, when items were presented sequentially, the effect of statistical decision noise will be different depending on how the search is performed. Thus, it will be useful to compare the amount of benefit by

sequential presentation across different types of load manipulation to investigate how perceptual load taps into attentional resources and how the search will be performed.

In the current study, perceptual load of search stimuli was increased in two different ways: A large number of search items were presented (set-size condition) or perceptual discrimination was more demanding with the smaller number of items (perceptual difficulty condition). As discussed already, in addition to perceptual load, the amount of statistical decision noise affects behavioral performance. For simplicity, it is assumed that statistical decision noise and perceptual load will have additive effects on task load (Palmer, 1994; Shaw, 1982). Thus, the total amount of load for a given task can be defined as the sum of perceptual load (attentional load) and additional load by statistical decision noise. The latter is not attentional, and not related to the capacity limit. If perceptual load is P and additional processing load by statistical decision noise is S, the total task load will be $P+S$. Obviously, as processing load increases, search accuracy will decrease. In the current study, search accuracy in the set-size condition and in the perceptual difficulty condition was equated, yielding equivalent task load. In the set-size condition, eight items were presented, and the total task load was set as P(perceptual load)$+S$ (load by statistical decision noise). In the perceptual difficulty condition, in which highly similar four items were presented, the total amount of load was also set as $P+S$.

Based upon this simple equation, there are several predictions about accuracy with sequential presentation in the set-size and perceptual difficulty conditions. First, it is possible that the search process will be parallel in both conditions. When items are presented sequentially, the number of items to be processed at a given time will be reduced, but statistical decision noise will not change. In the set-size condition, the perceptual load for each frame will be $P/2$ and statistical decision noise will be S. The task load for a single frame will be $P/2+S$. In the perceptual difficulty condition, the perceptual load for each frame will be $P/2$ and statistical decision noise will be S. In this case, the task load of the set-size condition with sequential presentation is identical to that of the perceptual difficulty condition. Secondly, the search might be done serially in both conditions, in which case statistical decision noise will also be reduced by one-half with sequential presentation in both conditions. Similar to the previous case, accuracy in both conditions will be the same because the task load for each frame would be equivalent ($P/2+S/2$). Finally, it is possible that search will be serial in the set-size condition, and parallel in the perceptual difficulty condition. When items are presented sequentially, statistical decision

noise will be reduced only in the set-size condition, and it will remain the same in the perceptual difficulty condition. The task load for each frame in the set-size condition will be *P*/2 (perceptual load) + *S*/2 (additional load by statistical decision noise) and the task load in the perceptual difficulty condition will be *P*/2 (perceptual load) + *S* (additional load by statistical decision noise). In this case, accuracy in the set-size condition will be higher than that in the perceptual difficulty condition.

Experiment 1

In Experiment 1, there were low load, set-size, and perceptual difficulty conditions, which were blocked. In the low load condition, four search items were presented and this condition served as baseline to confirm that the load manipulation was effective. In the set-size condition, the number of item was increased to eight. In the perceptual difficulty condition, perceptual discrimination of each item was more demanding with the same set-size as in the low load condition. Within each block, stimuli were presented either simultaneously or sequentially. When items were presented simultaneously, accuracy between set-size and perceptual difficulty condition was equated, yielding equivalent task loads across these two conditions.

Method

Participants Twelve participants were recruited from the Vanderbilt community. Informed consent was obtained. All participants were naïve of the purpose of the experiment.

Stimuli and Apparatus The experiment was programmed and run using MATLAB with the Psychophysics toolbox extension on an Intel Macintosh computer. Search items were presented on a black screen. Participants were required to find a 'T' rotated 90° to the left or right among rotated L-shaped distractors (each stimulus subtended 1° visual angle) and report the identity of the target. Search items were gray. In the perceptual difficulty condition, distractors were designed to be more similar with the target by increasing the offset in the line junction of distractors (Jiang & Chun, 2001). The target and distractors were positioned along an imaginary circle with a radius of 5.5°. There were eight evenly spaced positions on the circle. In the set-size condition, a search item occupied every position. In the low load and perceptual difficulty conditions, one of two positions in each quadrant was randomly selected.

Design & Procedure There were three load conditions, and their presentation order was

blocked. In the low load condition, four items were presented, and in the set-size condition, eight items were presented. The display in the perceptual difficulty condition was identical to that in the low load condition, except that distractors were more similar with the target than they were in low load condition.

In the practice, participants were given total

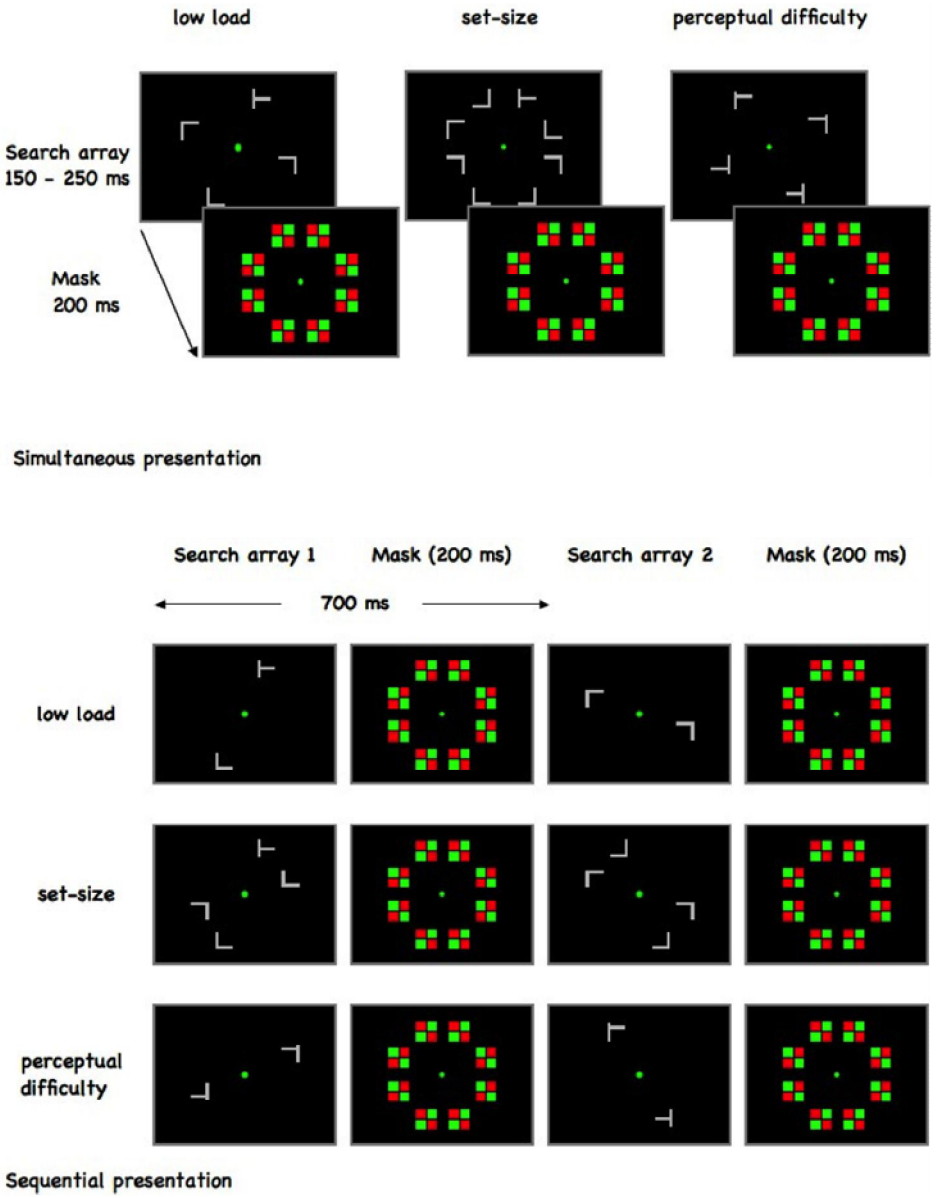

Figure 1. Examples of trials in Experiment 1.

240 trials, and search items were always presented simultaneously. Practice consisted of two sessions. During the first session, eight items were presented and duration of search item was adjusted to yield about 75% accuracy. Search display duration ranged from 150 ms to 250 ms, which is short enough to preclude eye movements. After the optimal duration of search stimuli was measured, another session followed. In this second session, four similar items were presented and search duration was defined as the adjusted duration from the previous practice session. Only the size of offset in line junction was adjusted to yield 75% accuracy.

In the experiment, each trial began with a 400-ms presentation of a fixation dot, followed by the search display. In each block, half the search items were presented simultaneously and half were presented sequentially, and presentation order was randomized. In the simultaneous presentation, every stimulus was presented at once for the duration adjusted from practice session. In the sequential presentation, search items were presented across two frames. In the set-size condition, two items were presented in two quadrants for each frame (top-left and bottom-right, or top-right and bottom left). In the low load and perceptual difficulty conditions, one item was presented in two quadrants. Each frame was presented for equal duration of simultaneous presentation. SOA from the onset of first frame to the onset of second frame was 700 ms. Each display was followed by a 200-ms presentation of masks. After the mask presentation, a blank screen followed. Search accuracy was emphasized over speed. The participants responded only after all the search stimuli were presented. The procedure is shown in figure 1. There were 15 blocks of 64 trials. The first three blocks were not included in the analysis.

Results and Discussion

Search accuracy was analyzed in a 2-way repeated measures ANOVA with load (low load, set-size, perceptual difficulty) and presentation type (simultaneous, sequential) as factors. The result showed a significant main effect of load, $F(2,22) = 28.163$, $p < .01$. The main effect of presentation type was also significant, $F(1,11) = 69.657$, $p < .01$. In the sequential presentation, participants were able to concentrate limited resources on just half of search items in order to increase accuracy. Importantly, the interaction between the load and presentation type was significant, $F(1,11) = 6.472$, $p < .05$. Specifically, while there were significant benefit by sequential presention in all the load conditions, p's $< .01$, the performance benefit by the sequential presentation was significantly greater for the set-size condition than for the

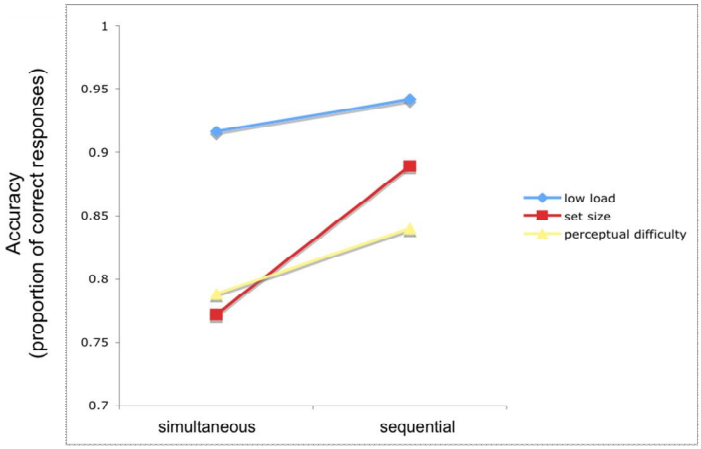

Figure 2. The results of Experiment 1.

other two, p's < .05. This pattern is consistent with the prediction that search would be serial with set-sizes larger than four, and it would be parallel at a set-size of four regardless of perceptual difficulty.

Experiment 2

In Experiment 1, in the set-size condition, presenting items sequentially did not only reduce the number of items for a given period of time, but any lateral interference from nearby distractors was also removed. This would magnify the benefit by sequential presentation in the set-size condition. This alternative was tested in Experiment 2.

Method

The design of Experiment 2 is identical to that of Experiment 1 except for the following differences. In Experiment 2, eight positions on the imaginary circle were split by an invisible diagonal line running from the top-right corner to the bottom-left corner, or from the top-left corner to the bottom-right corner. In the set-size condition, when search items were presented sequentially, items were presented in the upper or lower part. An example is shown in figure 3. Importantly, the second set of items could be presented in the locations of the first set of items, in order to preclude possible eye movements based upon expectations of search item locations.

Results and Discussion

Search accuracy was analyzed in the same manner as in Experiment 1. The main effect of load was significant, $F(2,22) = 60.252$, $p <$

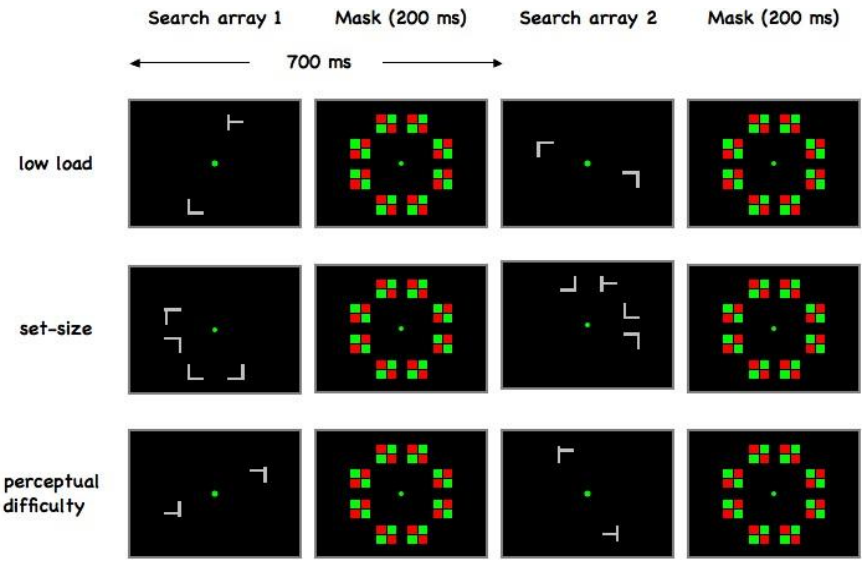

Figure 3. An example of sequential presentation trials in Experiment 2.

.01, as was the main effect of presentation type, $F(1,11) = 36.189$, $p < .01$. Importantly, the interaction between the load and presnetation type was significant, $F(1,11) = 5.092$, $p < .05$. Thus, the larger benefit by sequential presentation in the set-size condition was not due to reduced lateral interference by nearby distractors.

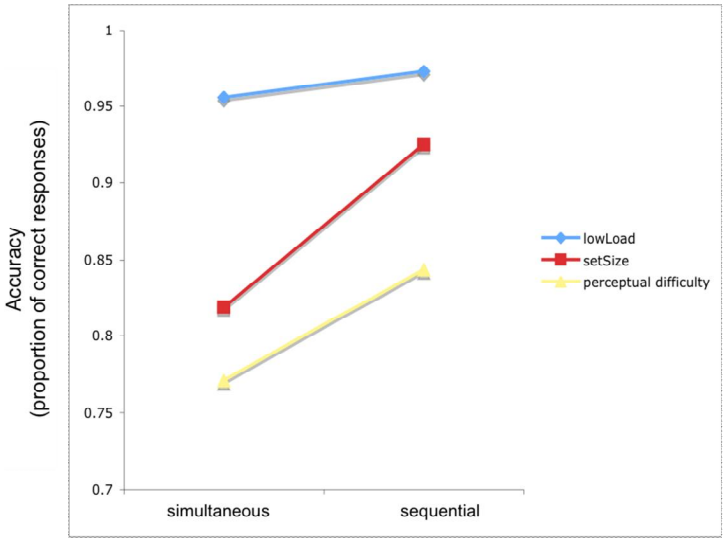

Figure 4. Experiment 2 results.

Experiment 3

Experiment 3 was designed to rule out another alternative. The reduced benefit of sequential presentation in the perceptual difficulty condition may have resulted from data-limits induced by increased perceptual difficulty. To test this alternative, we used a cuing paradigm. If our manipulation of perceptual difficulty induces data limits, the cuing benefit will be smaller in the perceptual difficulty condition, and the same interaction between load and presentation type should be observed.

Method

Method of Experiment 3 is identical to Experiment 1, with the following exceptions: Instead of using a sequential presentation in half of the trials, two green boxes were presented at top-left and bottom-right or top-right and bottom-left, 700 ms before the search array onset. These boxes always predicted target locations. (A schematic of a trial is shown in figure 5.) Cuing allows participants to concentrate resources on only cued locations. Thus, in cued trials, the set-size was conceptually reduced in half in both the set-size and perceptual difficulty conditions.

Results and Discussion

Search accuracy was analyzed in the same manner as in previous experiments. The main effect of load type and presentation type was

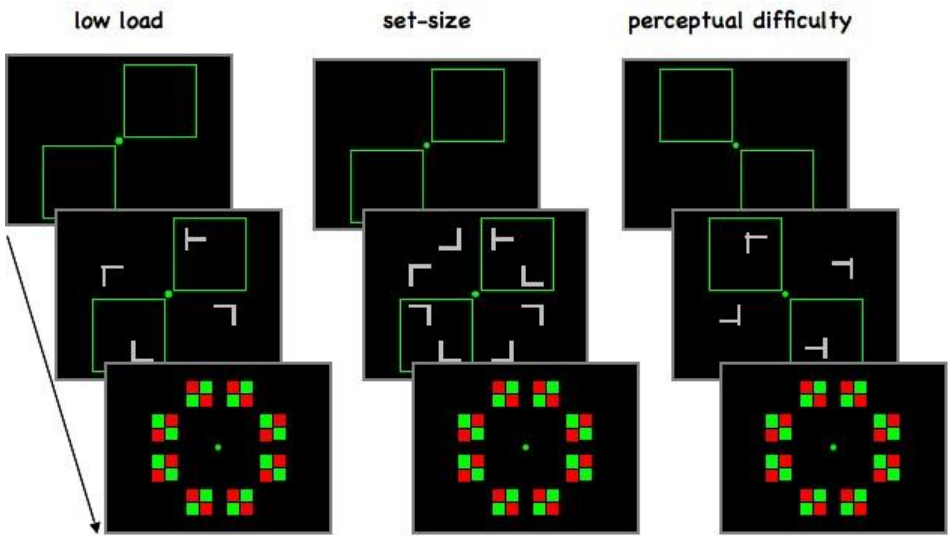

Figure 5. Example of cued trials in Experiment 3.

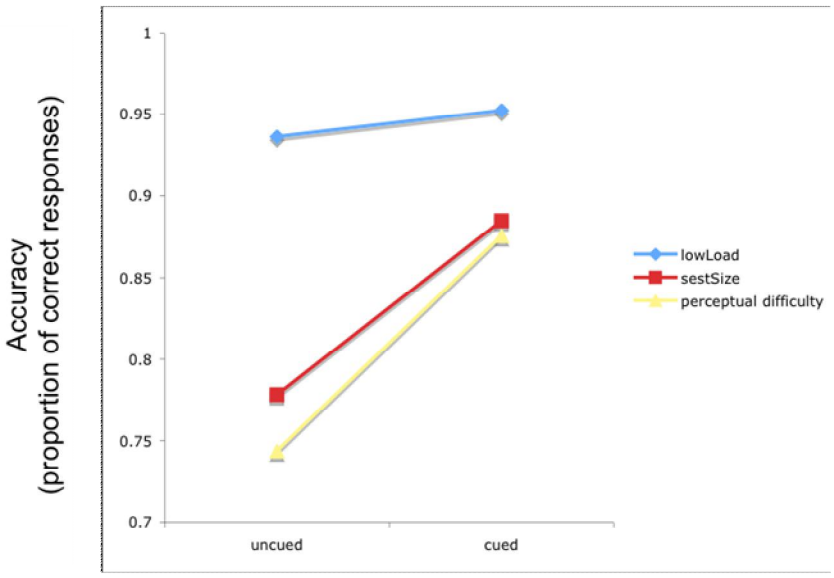

Figure 6. Experiment 3 results.

significant. The magnitude of the cuing effect did not differ significantly between the set-size and perceptual difficulty conditions, $p>.20$. This result demonstrates that the smaller benefit by sequential presentation in the perceptual difficulty condition was not due to data limitations. By focusing attentional resources on a smaller number of items, behavioral impairments induced by increased perceptual difficulty could be resolved as well as in the set-size condition.

General Discussion

The current study showed that the type of load manipulation and task strategy used in a sequential presentation task could manipulate the magnitude of performance. The amount of benefit in sequential presentation was greater when there was a large number of items in the search array than when perceptual discrimination was more demanding with a small number of items. Taking into account statistical decision noise as one of the factors influencing search accuracy, we suggested that the search process would be serial when the set-size exceeds four, and it would be parallel when the set-size is less than four, even with increased perceptual difficulty.

Although the current results provide converging evidence for the existence of a fixed number of processing channels, we are not arguing that attentional resources are strictly limited by the number of items: The capacity of

attentional resources can be set both by the number of items and the attentional resolution required for fine discrimination (but see Zhang & Luck, 2008). This was clearly shown throughout all the experiments. In both set-size and perceptual difficulty conditions, there were significant performance benefits when the search items were presented sequentially. Especially in Exp 3, attentional resources could be flexibly allocated to only two locations to resolve the capacity limit induced by perceptual difficulty. However, we are not suggesting that the number of items to be processed and attentional resolution can be completely traded off one-another. This flexible resource theory cannot explain why the amount of benefit by sequential presentation was larger in the set-size condition. The results of Experiment 3 also suggested that the interaction between load type and the amount of benefit afforded by sequential presentation was not due to data limits: A common limited pool of resource would be exhausted by increased set-size and perceptual difficulty, but in different ways. At the very least, set-size would be the factor determining whether the search should be performed in parallel or serially.

In addition, there is another important point to be mentioned. Using a cuing paradigm (Exp 3), we provided the evidence that attentional resource could be flexibly allocated to only two items. We interpret this result to indicate that attentional resources were concentrated on only two channels to enhance resolution, which is consistent with the slot+resources model of Zhang and Luck (2008). According to Zhang and Luck, however, our results in Exp 3 can also be explained by assuming that all of four channels were activated to process two items (slot+averaging model). If all four channels were activated and two stimuli were sampled twice, the participants would report the average of the representations in all channels, which would increase accuracy as slot+resources model predicted. Although Zhang and Luck 's study was designed to investigate visual working memory capacity, and it should be proven that their theory could also be applied to visual search, further investigation is necessary to clarify this issue.

To conclude, we are suggesting that selective attention would resolve information overload in different ways depending on how load was manipulated. Faced with large number of items to be processed (more than four), attentional resources will be allocated serially for each subset of inputs. No serial processing will be deployed when finer resolution is required, unless the set-size exceeds four.

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자극 개수와 해상도가 시각탐색의 부하효과에 미치는 영향

한 석 원

충북대학교 심리학과

Department of Psychology, Vanderbilt University

동시-순차 제시 패러다임을 이용하여 다른 종류의 부하 효과조건에서 시각 탐색과제 수행을 위한 주의자원이 어떻게 할당되는지, 구체적인 탐색 과정이 어떠한 방식으로 이루어지는지 살펴보았다. 이를 위해 탐색 자극의 부하를, 자극의 개수 혹은 자극간 유사도를 변화시켜 조작하였다. 탐색 자극이 순차적으로 제시되었을 때 수행이 좋아졌는데, 이러한 순차 이득은 자극의 개수가 늘어났을 때에 자극간 유사도가 늘어났을 때보다 더 컸다. 시각 탐색의 수행 수준은 지각적 부하와 결정 처리 방식에 따라 달라진다는 것을 볼 때, 본 결과는 이를 통해 자극 개수가 늘어났을 때는 순차처리 그렇지 않을 때는 병렬처리가 일어난다는 가정을 지지하였다.

주제어 : 시각 탐색, 용량제한, 순차 처리, 병렬 처리