Search for capacity-limited and super-capacity search

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Abstract

The present study investigated capacity limitations of visual search. In a series of experiments, participants searched for a singleton target among homogenous distractors, a conjunction target defined by combination of two features, or a feature target among heterogeneous distractors. Using the simultaneous-sequential paradigm, I found that singleton search proceeded in a capacity-unlimited manner. By contrast, the performance of the conjunction search was found to depend on a capacity-limited process. For feature searches, the performance of searching for a specific color was not affected by how the stimuli were presented, while the orientation search performance was enhanced as the number of distractors simultaneously presented with the target increased. These results imply that distinct colors are individually coded, whereas multiple orientations are encoded as an ensemble in a structured way. Taken together, the present study clarifies which type of search process are capacity-limited, and reveals how this limit can be overcome.
The visual search paradigm has been predominantly used to study visual perception and attention. A seminal study using this paradigm showed that the process of searching for a singleton target among an array of homogenous distractors is capacity-unlimited, whereas locating a target defined by a combination of two simple features (e.g., color, orientation, and size) depends on capacity-limited attentional process (Treisman & Gelade, 1980). Specifically, when participants searched for a singleton target, search performance was invariant, regardless of how many search items were presented. By contrast, when participants searched for a conjunction target, formed by combining two different features, search performance suffered as the number of items in the search display (set size) increased.

While measuring the set size effect has been useful to reveal the capacity-limited nature of visual perception, different groups of researchers have criticized that this approach often provides a misleading conclusion (Duncan, 1980; Duncan & Humphreys, 1989; Eckstein, Thomas, Palmer, & Shimozaki, 2000; Geisler, 1989; Geisler & Chou, 1995; Huang & Pashler, 2005; Palmer, 1994; Palmer, Ames, & Lindsey, 1993; Verghese, 2001). According to some of these, there are at least two factors responsible for a significant set size effect, which is not related to capacity limitations: statistical decision noise and eye movement. Specifically, 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 should increase as the number of items in the display increases. In the presence of this statistical decision noise, search performance would suffer especially
when many items are presented in the display, even though all those stimuli are processed with unlimited capacity.

Related to this, when the quality of sensory inputs is poor, participants would move their eyes to fixate on each search item. As there are many search items, the number of eye movements should also increase. In this case, even though the search process by itself is capacity-unlimited, increasing set size would lengthen search RT. This should be so even in the case that increasing the number of search items in the display actually aids the performance of a search task. Specifically, when the detection of the target is accomplished by co-activation of multiple search items, search performance should be enhanced as the search set size increases (Townsend & Nozawa, 1995). However, the presence of eye movement obscures this super-capacity nature of the search.

To circumvent these caveats and clarify the capacity-related nature of a given search process, many groups of researchers employed the simultaneous-sequential paradigm (Duncan, 1980; Huang & Pashler, 2005; Scharff, Palmer, & Moore, 2011, 2013). In this paradigm, search stimuli are presented in two different ways. In a type of trial, the simultaneous presentation trial, all the search stimuli are briefly presented at the same time. In the other, the sequential presentation trial, only a half of the stimuli are briefly presented first. Then, after a certain period of interval, the other half is presented. If the target search is a capacity-limited process, the search performance should be better in the sequential presentation condition than in the simultaneous presentation condition because the limited capacity allocated to each item at a given time is twice
greater in the former than in the latter. Importantly, the two conditions include the same number of search items, equating the amount of statistical decision noise. Hence, if the performance of a search benefits from the sequential presentation, this clearly shows that the search is capacity-limited.

Using this paradigm, it was found that the processes of searching for a size singleton target and a size-orientation conjunction target were capacity-unlimited, even though these searches yielded significant set size effects in RT (Huang & Pashler, 2005). Other researchers found that searching for a high-contrast stimulus among low-contrast stimuli and searching for a specific 2-D shape among heterogeneous distractors were also capacity-unlimited (Scharff et al., 2011, 2013). That is, the performance of the search tasks listed above did not benefit from the sequential presentation. By contrast, the processes of searching for a 3-D object and one’s own face were found to be subject to capacity limitations (Han & Jung, 2016; Scharff et al., 2011, 2013).

Expanding these studies, here I tested whether searches for an orientation singleton and a color singleton are capacity-limited or -unlimited by measuring the sequential presentation benefit. One important difference of the present study from previous studies is that the sequential presentation benefit was simultaneously measured with the set size effect within a single experimental session (Han & Jung, 2016). Specifically, in the experiments, there were three different types of trials: set size 4, set size 8, and set size 8-sequential trials. In the set size 4 and set size 8 trials, four and eight search items were
simultaneously presented, respectively. In the set size 8-sequential trials, a set of four items were presented, followed by the presentation of the other set.

Including these trial types in a single experimental session does not only allow me to test whether a given search is capacity-limited or not, but also to identify super-capacity search. Specifically, if a search task yields no set size effect, that is, no difference is found between set size 4 and set size 8 trials, this finding naturally leads to the conclusion that the search is capacity-unlimited. Certainly, the performance of this search task should not differ between the set size 8 and set size 8-sequential trials, either.

Another case to consider is that the search yields a significant set size effect, such that performance for set size 4 trials is better than for set size 8 trials. In this case, this set size effect could be either due to capacity limitation or due to statistical decision noise. This can be easily clarified by examining whether there is a performance difference between set size 8 and set size 8-sequential trials. If no difference is found between these two types of trials, the observed set size effect should be due to decision noise. By contrast, if search performance benefits from the sequential presentation, this provides unequivocal evidence that the search is capacity-limited.

It is also possible that search performance is better for set size 4 trials than for set size 8 trials. The performance enhancement by increased set size is interpreted that the search process depends on co-activation of the entire search items (Townsend & Nozawa, 1995). Contrary to the cases listed above, there could be a search task, in which the determination of the presence/absence of
the target stimulus is accomplished through the integration of separate analyses for each individual search item (Townsend & Nozawa, 1995). The performance of this kind of search, classified as 'super-capacity' search, should benefit from increasing set size, but should be impaired by the sequential presentation of the search stimuli, as the latter should disrupt the integration process.

Notably, a previous study also took a similar approach (Huang & Pashler, 2005). However, in that study, the set size effect and the sequential presentation benefit were measured in different ways; while the set size effect was measured by RT in the condition in which the search items were presented until responses, the sequential presentation benefit was measured by perceptual sensitivity under the brief stimulus presentation. This was appropriate because the goal of that study was to critically evaluate the claim that a significant RT set size effect indicates that the search is capacity-limited. However, given that the set size effect in RT is often overestimated presumably due to eye movements (Huang & Pashler, 2005; McElree & Carrasco, 1999), it is possible that a search yielding significant set size effect in RT would not yield a substantial amount of set size effect in perceptual sensitivity under the brief stimulus presentation. A stringent test for capacity limits of a search should simultaneously assess the set size effect and the sequential presentation benefit by a common measure.

Using the same procedure, I also investigated whether searching for a target stimulus defined by conjunction of a color and an orientation depends on capacity-limited attentional resources. Indeed, the Huang and Pashler study showed that the performance of a conjunction search did not benefit from the
sequential presentation benefit, suggesting that this kind of search proceeds in a capacity-unlimited manner (Huang & Pashler, 2005). This is a contrasting result with an earlier study regarding the same issue. Specifically, a study by McElree and Carrasco, employing the speed-accuracy tradeoff analysis (SAT), showed that conjunction search was capacity-limited (McElree & Carrasco, 1999).

Which factor is responsible for this discrepancy? One important point to consider is that McElree and Carrasco used a color-orientation conjunction target, while Huang and Pashler used a size-orientation conjunction target. Noteworthily, the target defined by the combination of a specific size and an orientation should produce a unique 2-D shape, which can be identified without combining two features. Crucially, a study by Scharff and colleagues demonstrated that the process of searching for a unique 2-D shape was capacity-unlimited (Scharff et al., 2013). Given these, the present study tested whether searching for the target defined by the combination of an orientation and a color, which does not produce a unique 2-D shape, would benefit from the sequential presentation.

Finally, I examined how searches for feature targets, which are readily discriminable from heterogeneous distractors, are performed. Specifically, I had participants search either for an orientation target or for a color target among an array of heterogeneous distractors. Contrary to the singleton searches, the targets were readily discriminable from distractors. These kinds of search tasks are known to yield strong set size effects in RT (Duncan & Humphreys, 1989; Wolfe, Friedman-Hill, Stewart, & O'Connell, 1992). I investigated how these
searches are performed under the brief stimulus presentation to clarify whether these are capacity-limited, -unlimited, or super-capacity searches.

Experiment 1a & 1b

Methods

Participants

Two groups of ten adults (eight males, 18-25 years) with normal or corrected-to-normal vision participated in Experiment 1a and Experiment 1b for course credit. To determine the sample size, I considered the sample size (N=8) of a previous study using a similar paradigm (Huang & Pashler, 2005) and ran a power analysis based upon a dataset from another published study (Han & Jung, 2016). This analysis revealed that N of 10 should be enough to detect a significant effect at the level of .80. Informed consent was obtained from each participant.

Stimuli and Apparatus

The experiment was programmed and run using Psychopy (Peirce, 2007). In Experiment 1a, the search stimuli, colored circles (radius: 1°) were presented on a 21-in. LCD monitor with a black background. Participants were required to fixate on a small white (0.3° x 0.3° of visual angle) dot presented at the center of the screen throughout the experiment. The target was a red circle (RGB: 255, 0,
0), while distractors were orange circles (RGB: 255, 127, 0). The search stimuli were covered by color patch masks.

In Experiment 1b, the search stimuli were Gabor gratings (1.25° x 1.25° of visual angle) of high contrast (100 %) against a gray background. The target was a grating tilted to the left or right by 15 degree, while distractors were vertical ones.

**Design and Procedure**

As shown in Figure 1, a trial started with a 500-ms fixation presentation, followed by the search display presentation. A half of all trials contained the target, while there was no target in the other half. Participants indicated the presence/absence of the target via button presses. They were instructed to respond as accurately as possible without time pressure. The duration of search display was individually adjusted prior to the main experimental session to yield about 70-80 % target accuracy when there were eight search items simultaneously presented (set-size 8 condition, see below). Notably, to achieve this level of performance for Experiment 1a, the stimuli had to be covered by masks, which were presented for 200 ms. To prevent eye movements, the longest search duration was set to 200 ms (Huang & Pashler, 2005). The resulting stimulus duration ranged from 25 ms to 200 ms. After the offset of the entire search display, participants were prompted to indicate whether the target was present or absent.
There were three presentation conditions: set size 4, set size 8, and set size 8-sequential conditions (Han & Jung, 2016). In the set-size 4 and set size 8 conditions, four and eight search items were simultaneously presented, respectively. In the set-size 8-sequential condition, two different sets of stimuli, each of which included four search stimuli, were sequentially presented across two frames with a 500-ms inter-frame interval. Notably, in the set-size 4 condition, two pairs of stimuli were always presented in two opposing quadrants (top-right and bottom-left or top-left and bottom-right, see Figure 1). Similarly, in the set size 8-sequential condition, the stimuli were always distributed in two opposing quadrants for a single frame. This was to prevent that manipulating set size and presentation type affect stimulus density and potential crowding effect between the stimuli (Han & Jung, 2016).

A total of 576 trials were divided into 6 experimental blocks. There were 192 trials for each presentation type. To analyze data from each experiment, I applied a repeated measures one-way ANOVA to perceptual sensitivity (d' prime) data with presentation type (set size 4, set size 8, set size 8-sequential) as a factor. Notably, the results did not differ when the analysis was applied to the accuracy data. The patterns of the hit rate and false alarm data also conformed to the d' prime data. Significant main effect was further tested by t-tests. Statistical thresholds of these were corrected for multiple comparisons using FDR procedure.
**Figure 1.** Trial design of Experiment 1a (a) and 1b (b). There was no mask in Exp. 1b.
Results and Discussion

The results of Experiment 1 are shown in Figure 2 (see also Table 1 for hit rate and false alarm rate data). A repeated measures one-way ANOVA with presentation type (set size 4 vs. set size 8 vs. set size 8-sequential) as a factor was separately applied to perceptual sensitivity data (d prime) from Experiments 1a and 1b.

The main effect of presentation type was significant in Experiment 1a, F(2, 18) = 9.26, p < .005. The analysis of Experiment 1b data also showed a similar pattern, F(2, 18) = 7.31, p < .005. Subsequent pairwise t-tests revealed that mean perceptual sensitivity for the set size 4 trials was significantly better than for the other trials in both experiments, p's < .05, corrected, while there was no difference between the set size 8 and set size 8-sequential trials, p's > .34.

The results of Experiments 1a (color singleton search) and 1b (orientation singleton search) are clear. The present singleton search tasks were demanding, such that robust set size effects in perceptual sensitivity were found in both experiments. However, the performance of the singleton searches did not benefit from the sequential presentation. The lack of significant sequential presentation benefit was not due the lack of statistical power; in both experiments, highly significant set size effects were found (see above). These results suggest that singleton search, even though the search task yields a robust set size effect, takes place in a capacity-unlimited manner. The set size effect observed in the present experiments should be primarily due to statistical decision noise.
The present finding is consistent with a number of previous studies arguing that singleton search is capacity-unlimited (Huang & Pashler, 2005; Mazyar, van den Berg, & Ma, 2012; Mazyar, van den Berg, Seilheimer, & Ma, 2013; McElree & Carrasco, 1999; Scharff et al., 2011; Treisman & Gelade, 1980). What is novel in the present study is that the set size effect and the index for capacity limit, sequential presentation benefit, were simultaneously assessed by a common measure within a single experimental session. By doing so, I verified that the employed search target was not readily discriminable from distractors and confirmed that searching for such a target proceeded in a capacity-unlimited manner.

Figure 2. Results of Experiment 1. a) Exp. 1a - Color singleton search. b) Exp. 2b - Orientation singleton search. Error bars represent standard errors of the mean.
Table 1. Hit and false alarm (FA) rate data for Experiment 1. Standard deviations are in parentheses.

<table>
<thead>
<tr>
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<th>Exp. 1a</th>
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<th>Exp. 1b</th>
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<tbody>
<tr>
<td></td>
<td>set size 4</td>
<td>set size 8</td>
<td>set size 8-sequential</td>
<td>set size 4</td>
<td>set size 8</td>
<td>set size 8-sequential</td>
</tr>
<tr>
<td>Hit rate</td>
<td>0.79 (0.12)</td>
<td>0.70 (0.11)</td>
<td>0.78 (0.08)</td>
<td>0.85 (0.19)</td>
<td>0.81 (0.18)</td>
<td>0.77 (0.17)</td>
</tr>
<tr>
<td>FA rate</td>
<td>0.18 (0.14)</td>
<td>0.17 (0.14)</td>
<td>0.22 (0.13)</td>
<td>0.24 (0.15)</td>
<td>0.31 (0.19)</td>
<td>0.21 (0.13)</td>
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Experiment 2

Experiment 1a and 1b showed that the performance of singleton searches did not benefit from the sequential presentation even though these searches yielded robust set size effects. Experiment 2 tested whether a similar result would be found in a conjunction search task. Indeed, previous studies reported mixed results regarding this issue. In line with the original claim by Treisman and Gelade (Treisman & Gelade, 1980), a study by McElree and Carrasco, adopting the speed-accuracy tradeoff analysis, argued that searching for a color-orientation conjunction target depended on a capacity-limited process (McElree & Carrasco, 1999). By contrast, Huang and Pashler, using the simultaneous-
sequential paradigm, found that the process of searching for a size-orientation conjunction target was capacity-unlimited (Huang & Pashler, 2005); they found no sequential presentation benefit in the size-orientation conjunction task.

The absence of sequential presentation benefit in the Huang and Pashler study might be due the nature of the conjunction target. Notably, the target defined by the combination of a specific size and an orientation should produce a unique 2-D shape. Given that the process of searching for a specific 2-D shape was found to be capacity-unlimited (Scharff et al., 2013), it remains to be clarified whether other kinds of conjunction targets, which are not discriminable from distractors solely by their shapes, are detected in a capacity-limited or -unlimited manner. To address this issue, the present experiment used the search target defined by the combination of a color and an orientation, as in the study by McElree and Carrasco.

Methods

Participants

A group of ten adults (seven males, 18-25 years) with normal or corrected-to-normal vision participated for course credit. Informed consent was obtained from each participant.

Stimuli and Apparatus
The same stimuli and apparatus as Experiment 1a and 1b were used except for the followings. The target was a red, 45 degree-tilted grating, which was tilted to the left or right. The distractors comprised red, vertical gratings and green, 45 degree-tilted gratings (Figure 3).

*Design and Procedure*

The details were identical to those of Experiment 1.

![Figure 3](image)

**Figure 3.** Trial design of Experiment 2. An example of set size 8 trial is shown.

*Results & Discussion*

The results of Experiment 2 are shown in Figure 4 (see Table 2 for hit and false alarm rate). A repeated measures ANOVA applied to perceptual sensitivity data revealed that the main effect of presentation type was significant, \( F(2, 18) = \)
20.95, \( p < .001 \). Pairwise t-tests showed that perceptual sensitivity for set size 4 trials was significantly better for set size 8 trials, \( t(9) = 7.54, p < .001 \), corrected. Importantly, perceptual sensitivity for the set size 8 sequential trials was also significantly better than for the set size 8 trials, \( t(9) = 2.76, p < .05 \), corrected. This result suggests that the process of searching for a color-orientation conjunction target, unlike the size-orientation conjunction search, depends on a capacity-limited process. This finding is not only consistent with a previous result derived from the SAT analysis (McElree & Carrasco, 1999), but also fits well a recent study about feature binding (Bouvier & Treisman, 2010). Specifically, Bouvier and Treisman showed that reentrant, feedback signals from the prefrontal cortex was necessary for different features to be combined. This account suggests that the perception of feature conjunction is a process requiring top-down attention.

Notably, a significant performance difference was also found between the set size 4 and set size 8-sequential trials, \( t(9) = 3.62, p < .05 \), corrected. This result implies that the observed set size effect was not solely due to capacity limit. Presumably, increasing set size would strain the limited perceptual capacity, and also increase the amount of statistical decision noise. This is broadly consistent with previous studies pointing out decision noise as a factor responsible for the set size effect observed in conjunction search (Eckstein et al., 2000; McElree & Carrasco, 1999; Palmer, 1994; Verghese, 2001).
Figure 4. Results of Experiment 2. Error bars represent standard errors of the mean.

Table 2. Hit and false alarm (FA) rate data for Experiment 2. Standard deviations are in parentheses.

<table>
<thead>
<tr>
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<th>set size 4</th>
<th>set size 8</th>
<th>set size 8-sequential</th>
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<tbody>
<tr>
<td><strong>Hit rate</strong></td>
<td>0.80 (0.14)</td>
<td>0.71 (0.20)</td>
<td>0.75 (0.16)</td>
</tr>
<tr>
<td><strong>FA rate</strong></td>
<td>0.18 (0.11)</td>
<td>0.25 (0.15)</td>
<td>0.19 (0.14)</td>
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Experiment 3a & 3b

The final sets of experiments examined whether searching for a feature target among an array of heterogeneous distractors is subject to capacity
limitations of perception. In Experiment 3a, the task was to search for a red
grating among green, blue, and cyan gratings. In Experiment 3b, participants
looked for a 45 degree-tilted grating among an array of distractors, comprising
vertical and horizontal gratings.

Methods

Participants

Two groups of ten adults (five males, 18-25 years) with normal or
corrected-to-normal vision participated for course credit. Informed consent was
obtained from each participant.

Stimuli and Apparatus

The same stimuli and apparatus as Experiment 1a and 1b were used
except for the followings. As shown in Figure 5, in Experiment 3a, the target was
a red (RGB: 255, 0, 0) grating, while distractors were green (RGB: 0, 255, 0),
blue (RGB: 0, 0, 255) and magenta (RGB: 255, 0, 255) gratings. In Experiment
3b, the target was a 45 degree-tilted grating, which was tilted to the left or right.
The distractors comprised vertical and horizontal gratings.

Design and Procedure

The details were identical to those of Experiment 1.
Results & Discussion

The results of Experiment 3 are shown in Figure 6 (see Table 3 for hit rate and false alarm data). A repeated measures ANOVA applied to perceptual sensitivity data of Exp. 3a (color search) revealed that there was no main effect of presentation type, $F(2, 18) = 1.84$, $p > .18$. The lack of main effect was not because the present study was under-powered; as we stated earlier, the power analysis revealed that N of 10 should be sufficient to detect significant effect at the level of .80. Furthermore, pairwise t-tests showed that there was not even a trend of significant difference across the presentation types, $p$'s > .30. It is also important to point out the present performance level is far below ceiling; the overall proportion of correct responses was 82.4 %, indicating that the task was sufficiently demanding. These results suggest that the process of searching for a color-defined target, even though the task was substantially difficult, takes place in a capacity-unlimited manner. Furthermore, because the target was readily
discriminable from distractors, there was minimal amount of decision noise, yielding no set size effect.

The analysis of data from Experiment 3b showed a drastically different pattern of results. The ANOVA revealed a significant main effect, $F(2, 18) = 17.55, p < .001$. Pairwise t-tests showed that perceptual sensitivity for the set size 8 trials was significantly greater than for the other types of trials. Specifically, the orientation search performance was better for the set size 8 trials than for the set size 4 trials, $t(9) = 2.46, p < .05$, corrected, contrary to the results from the singleton search and conjunction search experiments. Another notable finding is that the sequential presentation of search stimuli yielded the worst performance, $p's < .05$, corrected.

These results can be explained by a unique nature of orientation processing. Specifically, there is evidence that multiple stimuli with distinct orientations are encoded as an ensemble, such that the perception of an individual orientation relies on the entire spatial structure of the stimuli (Huang, 2015a; Huang & Pashler, 2007; Huang, Treisman, & Pashler, 2007). Given this property, one can predict that distributed attention across the entire visual field, rather than focal attention, should be beneficial for determining whether a stimulus with a particular orientation is present or absent (Alvarez & Oliva, 2009; Chong & Treisman, 2005; Huang, 2015a).

The current finding fits well with this prediction; the orientation search performance was best when the number of items surrounding the target was greatest. Furthermore, when the spatial structure was disrupted by the sequential
presentation of the stimuli, the search performance severely suffered. Notably, a recent study also showed that this ensemble-based encoding is a perceptual principle, by which orientation perception is dominated. Hence, the present finding is consistent with and extend the findings by Huang (Huang, 2015b). Taken together, all these findings point to the role of ensemble coding to supersede the capacity limit of the visual system. Indeed, Townsend and Nozawa also pointed out that under some circumstances, the determination of the presence/absence of the target stimulus should be done by co-activating all the search stimuli and integrating the individual perceptual analyses of each item (Townsend & Nozawa, 1995). The performance of this kind of search, called ‘super-capacity’ search benefits from large set size. The present study illustrates that the orientation search is an example of super-capacity search.

Alternatively, the observed pattern of results could be because the current orientation search task was performed in a similar way with a texture segmentation task. Given the spatial arrangement of the search stimuli, the task can be accomplished by detecting a texture target that differs from the background. The performance of such a task was found to be impaired when attention was focused on the target stimulus because the heightened resolution by focal attention hinders the detection of the texture (Yeshurun & Carrasco, 1998, 1999)
Figure 6. Results of Experiment 3. a) Exp. 3a - Color feature search. b) Exp. 2b - Orientation feature search. Error bars represent standard errors of the mean.

Table 3. Hit and false alarm (FA) rate data for Experiment 3. Standard deviations are in parentheses.

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<th>Exp. 3a</th>
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<td>set size 4</td>
<td>set size 8</td>
<td>set size 8-sequential</td>
<td>set size 4</td>
<td>set size 8</td>
<td>set size 8-sequential</td>
<td>set size 4</td>
<td>set size 8</td>
</tr>
<tr>
<td>Hit rate</td>
<td>0.80 (0.07)</td>
<td>0.80 (0.08)</td>
<td>0.79 (0.08)</td>
<td>0.78 (0.14)</td>
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<tr>
<td>FA rate</td>
<td>0.11 (0.07)</td>
<td>0.08 (0.06)</td>
<td>0.11 (0.08)</td>
<td>0.25 (0.22)</td>
<td>0.18 (0.17)</td>
<td>0.30 (0.22)</td>
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General Discussion

The present study investigated capacity limitations of various types of visual search tasks. In five experiments reported here, I found that the performance of singleton searches did not suffer from capacity limitations of visual perception; the search performance was equivalent between when all the search stimuli were simultaneously presented and when the two subsets were sequentially presented, even though the target-distractor similarity was high, yielding robust set size effects. By contrast, the conjunction search was found to depend on capacity-limited attentional resources. When the target was a color-orientation conjunction stimulus, the search performance benefitted from the sequential presentations. Finally, when participants searched for readily discriminable targets from an array of heterogeneous distractors, drastically different patterns of results emerged. When the target was defined by color, the search performance was constant, regardless of set size and presentation types. However, the performance of searching for an orientation target was enhanced when many distractors were simultaneously presented with the target.

While the finding that singleton search was performed in a capacity-unlimited manner was also reported by other studies (Eckstein et al., 2000; McElree & Carrasco, 1999; Scharff et al., 2011; Treisman & Gelade, 1980), it has been controversial whether the searching for a conjunction target depends on a capacity-limited or -unlimited process. A study by McElree and Carrasco using
the SAT measure claimed that the process of searching for a conjunction target consumes capacity-limited attentional resources (McElree & Carrasco, 1999). By contrast, using the simultaneous-sequential paradigm, Huang and Pashler found no evidence for capacity limit in conjunction search (Huang & Pashler, 2005). One important discrepancy between these studies, besides the employed paradigm (SAT vs. simultaneous-sequential paradigm), lies in the types of feature conjunction used in the experiments; in the study by McElree and Carrasco, the target was a color-orientation conjunction stimulus, while Huang and Pashler used a size-orientation conjunction target. An important point to consider is that the combination of a particular size and orientation produces a target stimulus that has a unique 2-D shape, while the color-orientation conjunction does not. Notably, Sharff and colleagues reported that searching for a unique 2-D target among an array of heterogeneous distractors did not benefit from the sequential presentation (Scharff et al., 2013), suggesting that this kind of search is capacity-unlimited.

To unequivocally address the issue of capacity limit of conjunction search, the present study adopted the simultaneous-sequential paradigm, which yielded the result that conjunction search was capacity-unlimited (Huang & Pashler, 2005). However, Importantly, unlike the Huang and Pashler study, a color-orientation conjunction stimulus was used as the target. The result of this experiment was clear-cut; the conjunction search yielded a robust set size effect, and there was a significant performance benefit by the sequential presentation. This result supports the claim that searching for a feature conjunction target,
which is not discriminable from distractors solely by its shape, depends on capacity-limited attentional resources (Bouvier & Treisman, 2010; McElree & Carrasco, 1999; Treisman & Gelade, 1980).

The final sets of results are also remarkable. The process of searching for a specific color target among an array of heterogeneous distractors did neither suffer performance impairments by increasing set size, nor benefitted from the sequential presentation. This result suggests that a color target readily discriminable from distractors is not easily confused with non-target color distractors. In line with this, searching for such a target was not susceptible to capacity limit. This is consistent with a claim of the Boolean map theory, suggesting that color can be used to efficiently filter out non-target stimuli (Huang, 2015a; Huang & Pashler, 2007; Huang et al., 2007).

By contrast, the orientation search yielded a counterintuitive pattern of results. The search performance was greatest when multiple distractors were simultaneously presented with the target. This implies that the process of searching for an orientation target was accomplished by co-activating the target and surrounding stimuli (Townsend & Nozawa, 1995). Consistent with this proposition, the sequential presentation of search stimuli, which was beneficial for the conjunction search and did not impair the singleton and color searches, was devastating for the performance of orientation search task. These notable findings fit well with recent studies pointing out that multiple stimuli with distinct orientations are perceived as an ensemble (Alvarez & Oliva, 2009; Chong & Treisman, 2005; Huang, 2015a). By this nature, the perception of an individual
orientation should rely on encoding the entire spatial structure of the stimuli. Hence, when this spatial structure is disrupted by sequentially presenting the search stimuli, the performance should suffer. Furthermore, increasing the number of surrounding distractors should incentivize the deployment of global/distributed attention, which is optimal for encoding of an ensemble/spatial structure.

Alternatively, the orientation search result can be explained by the fact that the task was performed in a similar way with a texture segmentation task. In the current task setting, the presence/absence of the orientation target could be determined by examining whether a texture target, which differs from the background, is present in the display. Such a texture segmentation task was found to benefit from distributed attention (Yeshurun & Carrasco, 1998).

Taken together, the present study provides important insights about capacity limit of visual search and the nature of visual perception. First, detecting a singleton stimulus takes place in a capacity-unlimited manner. Second, the process of searching for a conjunction stimulus draws on capacity-limited attentional resources. Finally, two elementary features, color and orientation are encoded in differential ways; multiple orientations are encoded as an ensemble or a structure, whereas each distinct color is individually represented in the visual system.
Acknowledgements

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References


Figure
25 ~ 200 ms

present or absent?

Until response
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