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Spatial extent of attention and pop-out visual search with two targets

James Wilmott [1] & Joo-Hyun Song [1,2]

1. Department of Cognitive, Linguistic & Psychological Sciences, Brown University, Providence, RI 02912-1821
2. Carney Institute for Brain Science, Brown University, Providence, RI 02912-1821

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Correspondence to: James Wilmott

Department of Cognitive, Linguistic & Psychological Sciences

Brown University, Providence, RI 02912-1821

james_wilmott@brown.edu

Tel: 1-401-863-1528 (P)

Fax: 1-401-863-2255 (F)

Abstract

In daily life, visual scenes are often complex and crowded, where many objects can compete for attention and selection. Previous studies have demonstrated that the spatial extent of attention (distributed vs. focused) is allocated according to task demands in visual search. For instance, detection of a pop-out target is thought to suffice with broadly distributed attention across a visual scene, while discrimination of a target feature requires focused attention on a target. Much less is known about how distributed and focused attention modulate performance when an additional target is present. Here, participants were asked to detect an oddity target or discriminate its feature during pop-out visual search including one or two targets, where only one target was required to be found. We first observed that the presence of a second target facilitated detection but hindered discrimination. We further investigated what factors contribute to reduced two-target discrimination efficiency. We determined that the strength of perceptual grouping among homogenous distractors was weakened when two targets were present compared to one target. Additionally, we found that different responses rather than shapes between the two targets contributed more to interfere with discrimination. Taken together, our results show how pop-out search including two targets is modulated by the manipulation of spatial attention, perceptual grouping, and the compatibility of perceptual and response features.

Everyday visual scenes are often complex and crowded, where many objects can compete for attention and selection. To successfully interact in such environments, animals (including humans) often perform visual search to detect or identify relevant objects. Looking for a key on a messy desk, detecting predators, foraging for apples, and security screening at the airport are all examples of visual search. Visual search links what we do in our daily life to neural and behavioral mechanisms of the visual system and has implications in psychology, vision science, neuroscience, and ecology (Nakayama & Martini, 2011). Influential theories of visual search such as Feature Integration Theory (FIT) have evolved to explain what determines the accuracy and efficiency of detecting the presence of a single target among distractors (Treisman & Gelade, 1980). For instance, according to FIT there are two visual search modes. When a feature singleton such as color, orientation, or shape defines a target, reaction time is independent of the number of distractors in the search array. This flat search function is thought to indicate parallel processing of stimuli that occurs pre-attentively. In contrast, when conjunctions of multiple features define a target, reaction time increases with more distractors. The positive slope of this search function is thought to indicate a serial application of attention to each stimulus that is necessary to bind its features into a coherent object. FIT predicts conjunction search to be self-terminating, where the observer stops searching when a target is detected (Treisman et al., 1977; Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990; Triesman, 1988).

To further understand how visual attention operates for fast and accurate information processing, previous studies introduced a new paradigm that included an additional target (Estes & Taylor, 1966; Townsend, 1972; Holmgren, et al., 1974; van der Heijden, 1975; Townsend, & Ashby, 1982; Egeth & Mordkoff, 1991). For example, Pashler (1987) examined whether observers perform a serial self-terminating search to detect a conjunction target, as predicted by FIT. The presence of an extra target would facilitate self-terminating but not exhaustive search because a target should be found faster on average when there are more targets (Bjork & Estes 1971; Baddeley & Ecob 1973; van der Heijden & Menckenberg, 1974). Reaction time was substantially faster on two than one-target trials in the lower range of set sizes (e.g., 4 or 8 items). This appeared to be consistent with a self-terminating search. However, the ratio of the search function slopes for target-absent and target-present trials was close to 1:1, which could not be explained by a simple self-terminating search that should result in a 2:1 slope. These findings lead to an alternative hybrid account, in which observers perform serial self-terminating search over relatively large "clumps" of items, while limited-capacity parallel processing is involved for both small displays and small clumps (Pashler, 1987).

In addition, two-target paradigms have also been used in feature singleton detection tasks to determine how target signals from different feature dimensions are used during search (Krummenacher, et al., 2001, 2002). For instance, Krummenacher et al., (2001) observed that reaction times in trials including a pop-out target defined by two feature dimensions (orientation and color) were faster than those including a target defined individually by either dimension. In various previous studies, a similar reaction time advantage has been observed for cases when two identical targets (i.e., redundant targets) are present or when targets are defined by intra-dimensional redundancy (Holmgren, et al., 1974; Eriksen & Eriksen, 1974, 1979; Miller, 1982; van der Heijden, et al., 1984). Two mutually exclusive models have been proposed to explain this redundant target advantage. On one hand, independent parallel race models postulate that signals from multiple targets (or dimensions) are processed independently so that target detection is determined by the signal that wins the race (Raab, 1962). In contrast, co-activation models propose that signals from each target or dimension are summated at a stage before the response (Miller, 1982).

These previous studies using two targets have mostly demonstrated faster reaction times when two targets are present compared to one-target cases. These findings have provided substantial insight into the role of attention in modulating the temporal characteristics of information processing (e.g., serial vs. parallel, self-terminating vs. exhaustive, or race vs. coactivation). However, it is less known about how the spatial characteristics of attention, such as whether to allocate attention in a distributed or focused manner, interact with the processing of two targets during visual search. According to previous visual search studies, broadly distributed attention suffices to rapidly detect and localize a target but focal attention is necessary for fine-detail target feature discrimination (Atkinson & Braddick, 1989; Folk & Egeth, 1989; Green, 1992; Johnston & Pashler, 1990; Kristjansson, et al., 2001; Nakayama & Mackeben, 1989; Sagi & Julesz, 1985A, 1985B; Song & Nakayama, 2006). For example, Sagi and Julesz (1985a, 1985b) showed that when a mixture of horizontal and vertical line segments was presented among diagonal line segments, participants could rapidly count numbers of them and determine their positions independent of the number of targets. However, when discrimination between horizontal and vertical orientation was required to accurately report whether all line segments were the same orientation, more time was needed to allocate focal attention.

In the present study, we adopted the experimental paradigm developed by Bravo and Nakayama (1992) to manipulate whether distributed or focused attention is required for visual search. We then examined how the spatial extent of attention affects search performance when two targets are present. Here, we summarize Bravo and Nakayama's (1992) paradigm and the most relevant findings for the present study, which revealed distinctive visual search patterns associated with distributed and focused attention. They presented an odd-colored diamond target among homogeneous colored distractors, where target and distractor colors were randomly switched from trial-to-trial (pop-out search). When participants were required to detect the presence or absence of a target, reaction times were relatively fast and did not vary with distractor numbers, demonstrating a characteristic flat slope. This result suggested that when there are salient perceptual differences between the target and distractors, a broad scope of distributed attention is sufficient for target detection. However, when participants were asked to discriminate a detailed feature of the odd-colored target such as a tiny cut-off corner side, search time decreased as the number of distractors increased. They proposed that the perceptual grouping process of segregating the odd-colored target from distractors is more efficient with larger numbers of homogenous distractors, leading to faster allocation of focused attention to the target (Julesz, 1986; Koch & Ullman,1985).

To summarize, Bravo and Nakayama (1992) provided evidence that the spatial extent of attention can be modulated according to task demands. Thus, their paradigm establishes a tool to manipulate whether distributed attention across a stimulus array (detection) or focused attention on individual stimuli (discrimination) is required for a given visual search. Such diverging patterns between detection and discrimination pop-out search tasks have also been consistently reported in both humans and non-human primates (Kristjansson, et al., 2001; Nakayama & Mackeben, 1989; Song & Nakayama, 2006; Song, et al., 2008).

Here, we adopted Bravo and Nakayama's paradigm to manipulate the extent of spatial attention and varied the number of odd-colored targets (one vs. two). In Experiment 1, we examined whether the spatial extent of attention modulates visual search patterns differently when an additional odd-colored target is present. We observed that the presence of an additional target facilitated reaction time for target detection but slowed discrimination of a target's feature. This pattern of results indicates that an additional target can facilitate or deteriorate the efficiency of visual search. In Experiments 2 and 3, we further investigated which factors influence the efficiency of discrimination when two targets are present.

Experiment 1: Does the spatial extent of attention influence pop-out search including two odd-colored targets?

In Experiment 1, we examined whether the spatial extent of attention modulates patterns of pop-out search differently when an additional odd-colored target is present. Following Bravo and Nakayama (1992), we asked participants to perform both a detection task requiring distributed attention and a discrimination task requiring focused attention. On a subset of trials, two odd-colored targets were present. Note that when we presented an additional odd-colored target with the same color, we maintained the total number of stimuli in the display constant, in accord with previous studies (e.g., Eriksen & Eriksen, 1979; Krummenacher et al., 2001, 2002; Akyürek & Schubo, 2013). To our knowledge, performance in detection and discrimination tasks including two targets has never been directly compared using the same display.

Methods

Participants

Fifteen participants (7 female, mean age = 21) from the Brown University community volunteered to take part in this experiment for one hour in exchange for course credit or monetary compensation. All participants were right handed and had normal or corrected to normal vision and normal color vision. They were naïve to the goals of the experiment. The protocol was approved by the Brown University Institutional Review Board.

Apparatus

Stimuli were displayed at 72 Hz on a ViewSonic G90fB monitor running Windows XP (19-inch display, 1152 by 864 resolution). Eye position was measured using an Eyelink 1000 eye tracker (SR Research, Ottawa, Ontario, Canada).

Stimuli and procedure

Participants performed 3 blocks each of the detection (180 trials/block) and discrimination (120 trials/block) tasks. Three participants completed only 2 blocks of the detection task due to time constraints. The order of blocks alternated and was counterbalanced across participants. Each participant practiced a block of each task to start.

Detection task (Figure 1A, left column): At the beginning of each trial a gray cross appeared at the center of the monitor. The cross subtended 0.5° by 0.5° and had a luminance of 5 cd/m^2 presented against a black background of 0.03 cd/m^2. Participants were instructed to fixate the cross throughout the trial. They initiated a trial by pressing a key ('5'), which turned the cross white (26 cd/m^2), and continued to hold it until they made a response. Once a trial began, after 500 ms, six diamonds subtending 1° by 1° were displayed. On each target present trial, target color was randomly selected to be red or green (equiluminant at 29 cd/m^2) with distractors presented in the other color. During target-absent trials all stimuli were displayed in the same color. Within a block there were an equal number of target-absent, one-target (Figure 1A, left top), and two-target trials (Figure 1A, left bottom). Participants were asked to release the '5' key and press an assigned key with the same finger to report whether any odd-colored target (defined as the color that appeared less) was present ('8') or absent ('2'). Auditory feedback on response correctness was provided after each trial. Participants were instructed to respond as soon as they found the first target while being as accurate as possible. We discarded trials in which participants released the '5' key before the stimulus onset or failed to respond within 1500 ms and repeated them later in the block.

The position of each stimulus was randomized within the following constraints: 1) stimuli had to be within a 10° by 10° invisible square surrounding the center of the screen, 2) stimuli could not appear within 1.0° of each other, 3) no stimuli were presented within 1.5° of the vertical midline of the display, 4) three stimuli were presented to the left and right of the vertical midline, and 5) when a second target was presented, the distance between both targets was randomly selected with equal probability to be 3°, 5°, or 7° to prevent anticipation of the second target location. If a participant blinked or moved their eyes further than 1° from the cross the trial was immediately discarded and replaced later in the block.

Discrimination task (Figure 1A, right column): The procedure was identical to the detection task except for the following. On each trial, one (Figure 1A, right top) or two (Figure 1A, right bottom) odd-colored targets of the same color were presented, the number of which was randomly selected with equal probability. Each diamond had a 0.25° corner cut-off from the top or bottom that was randomly selected for each stimulus. Participants reported which corner was cut-off from an odd-colored target by pressing the '8' key (top corner cut-off) or '2' key (bottom corner cut-off). They were instructed to report as soon as they found a target even if two were displayed. On two-target trials, we randomized the cut-off corner of each target (top or bottom) so that the two targets had either the same or different cut-off side with equal probability. This led to two trial types where the target shapes and potential responses were identical (T_{same}) and opposite ($T_{different}$).

Data analysis

For each participant, we excluded trials from data analysis where the reaction time was more than 3 standard deviations away from the mean of each condition. Using this criterion, we excluded an average of 1.7% ± 0.1% (standard error of the mean, s.e.m.) of detection trials and 1.4% ± 0.1% of discrimination trials from each participant. We conducted repeated measure ANOVAs and applied Bonferroni correction for planned pairwise comparisons. Effect size was estimated using η^2 and Cohen's d. According to Cohen (1988), η^2 of 0.01, 0.06 or 0.13 corresponds to a small, medium and large effect. A Cohen's d of 0.2, 0.5, 0.8 is considered a small, medium, and large effect (Cohen, 1988; Lakens, 2013).

Results and Discussion

Detection task:

Overall, participant accuracy was high in all conditions: target-absent (96.5% ± 0.6% s.e.m.), one-target (98.7% ± 0.3%), and two-target (99.4% ± 0.2%). Accuracy was higher when at least one target was present compared to when there was no target. This was confirmed with a one-way repeated-measures ANOVA that revealed a significant main effect of number of targets

($F_{2,14} = 20.16$, $p < 0.005$, $\eta^2 = 0.38$) and pairwise comparisons between target-absent and one-target trials ($t_{14} = 5.04$, $p < 0.001$, $d = 1.3$) and target-absent and two-target trials ($t_{14} = 4.55$, $p < 0.001$, $d = 1.17$). However, one-target and two-target conditions did not significantly differ from each other after correction for multiple comparisons ($t_{14} = 2.31$, $p > 0.1$, $d = 0.6$).

When comparing reaction times, we excluded trials where the response was incorrect. Figure 1B (left) demonstrates that reaction times differed depending on the number of targets presented (absent, one, or two), which was confirmed by a one-way repeated-measures ANOVA ($F_{2,14} = 45.24$, $p < 0.001$, $\eta^2 = 0.17$). Further planned analysis indicated that reaction time on target-absent trials (gray) was slower than on one-target present trials (blue; $t_{14} = 5.44$, $p < 0.001$, $d = 1.4$) consistent with previous visual search studies (e.g., Treisman & Gelade, 1980; Bravo & Nakayama, 1992). Of interest was whether two targets (purple) facilitate or deteriorate visual search. We observed faster reaction time in the two-target trials compared to one-target trials (blue; $t_{14} = 4.65$, $p < 0.001$, $d = 1.70$). This result was consistent with prior studies using a similar singleton pop-out detection task (e.g., Krummenacher, et al., 2001, 2002, 2014; Töllner, et al., 2011; Zehetleitner, et al., 2009). Two-target trials (purple) were also faster than target-absent trials (gray; $t_{14} = 8.46$, $p < 0.001$, $d = 2.18$).

Discrimination task:

We compared accuracy of the one-target trials with the two-target trials in which both targets share the same cut-off side (T_{same}). This is because when each target had a different cut-off side ($T_{different}$), any of the two responses ('top' or 'bottom') would be correct, resulting in an inflated accuracy estimate. We observed significantly higher accuracy for one-target (94.2% ± 1.7%) compared to T_{same} trials (91.1% ± 1.9%; $t_{14} = 3.22$, $p < 0.01$, $d = 1.17$).

Figure 1B (right) shows the average reaction time for the one-target and two-target conditions in the discrimination task. Reaction time was slower in the two-target (purple) than one-target condition (blue; $t_{14} = 4.89$, $p < 0.001$, $d = 1.78$), which was the opposite of what we observed in the detection task. We further observed that both T_{same} (676 ± 15 ms; $t_{14} = 3.26$, $p < 0.01$, $d = 0.84$) and $T_{different}$ (721 ± 24 ms; $t_{14} = 4.91$, $p < 0.005$, $d = 1.27$) trials in the two-target condition were significantly slower than the one-target condition. For the two-target condition, one might think that the $T_{different}$ condition could be easier than the T_{same} condition because participants would be correct with either of the two responses ('top' or 'bottom'). However, reaction time in the $T_{different}$ condition was significantly slower compared to in the T_{same} condition ($t_{14} = 3.17$, $p < 0.05$, $d = 0.82$). We further examined in Experiment 3 whether this observed discrepancy between the T_{same} and $T_{different}$ conditions occurred because of different target shapes, associated responses, or both.

To summarize, in Experiment 1 we demonstrated that when more than one odd-colored target was present, target detection was facilitated. This result is consistent with prior studies that have demonstrated reaction time and accuracy gains when extra target stimuli are presented (Eriksen & Eriksen, 1979; Miller, 1982; Krummenacher et al., 2001, 2002). However, we also showed that target discrimination was hindered by an additional odd-colored target. At a first glance, these results appear to indicate that whether broadly distributed or narrowly focused attention is required for visual search modulates the effect of an additional target. In Experiments 2 and 3, we further investigated potential factors that might contribute to this inefficiency related to the two-target trials during discrimination.

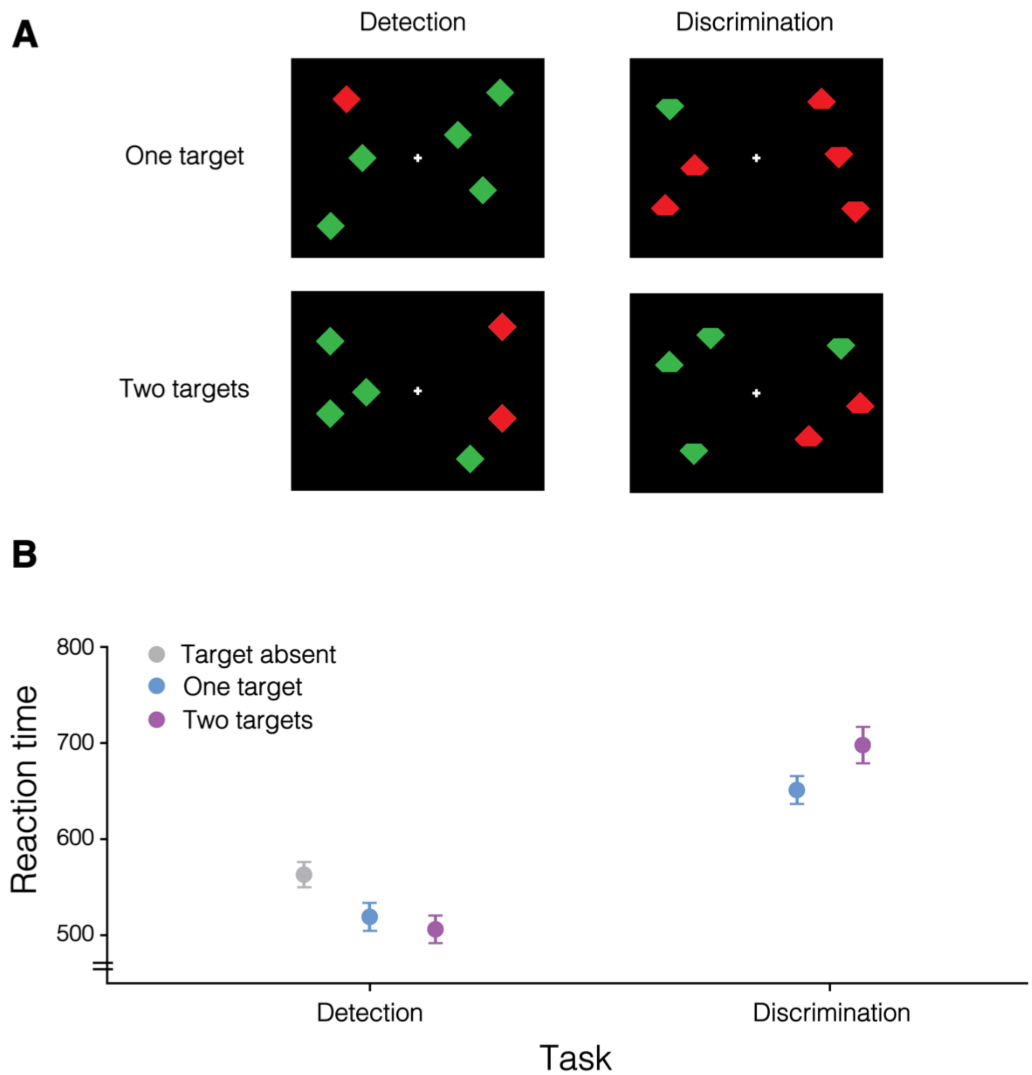

Figure 1. Tasks and results of Experiment 1. A. Representative displays. In both detection (left column) and discrimination (right column), one (top row) or two (bottom row) odd-colored targets were randomly presented among homogenously colored distractors. During detection, participants reported whether at least one odd-colored target was present or absent. Target-absent trials were also included, where all six stimuli were presented in the same color. During discrimination, participants reported whether the top or bottom corner was cut-off from one odd-colored target. On two-target trials, each target shape was randomly selected, resulting in trials

where targets were identical (same top or bottom cut-off corner) or opposite (one top and one bottom cut-off corner). Target color was randomly switched between red and green on each trial, with distractors presented in the other color. Stimuli positions were also randomized on each trial. **B. Mean reaction time as a function of the number of targets.** Results from the detection task are plotted on the left side and results from the discrimination task are plotted on the right side. Performance in target-absent trials (only in detection) are presented in gray, one-target trials are presented in blue, and two-target trials are presented in purple. While reaction time decreased for two-target trials during detection, it increased for two-target trials during discrimination. Error bars represent the between-participants standard error of the mean (s.e.m.).

Experiment 2: Does perceptual grouping contribute to slower reaction times during pop-out discrimination with two targets?

In Experiment 1, we held the total number of stimuli constant at six so that there was always one less distractor present on two-target trials than one-target trials, following prior studies with two targets that kept a constant display size (Eriksen & Eriksen, 1979; Krummenacher et al., 2001, 2002; Akyürek & Schubo, 2013). That said, the one less distractor on two-target trials may have affected search efficiency during discrimination. As discussed earlier, previous studies have shown that as the number of homogenous distractors increases, the strength of perceptual grouping is enhanced, which leads to faster allocation of focused attention to a target (Bravo & Nakayama, 1992; Julesz, 1981, 1986; Koch & Ullman, 1985; McPeek et al., 1999; Song & Nakayama, 2006). Thus, increased perceptual grouping facilitates the efficiency of odd-colored target discrimination but does not affect detection during pop-out search (Bravo & Nakayama, 1992; Nakayama & Joseph, 1998).

In Experiment 2, we assessed whether this one less distractor weakened perceptual grouping during discrimination, resulting in less efficient allocation of attention to a target and contributing to slowed reaction times on two-target than one-target trials. Perceptual grouping has been known to be a complex process that takes into account many aspects of stimuli, including proximity (Bacon & Egeth, 1991), shape (Duncan & Humphreys, 1989), color (Farmer & Taylor, 1980; Bundesen & Pederson, 1983), and orientation (Julesz, 1981). Thus, it would not be perfect, but we attempted to equate the strength of perceptual grouping between one-target and two-target displays during discrimination by matching the targets to distractors ratio. For example, at a targets to distractors ratio of 1:2, displays would contain either one target and two distractors or two targets and four distractors. If an unequal strength of perceptual grouping between one-target and two-target trials primarily contributed to the longer reaction times in Experiment 1, we expected to observe a diminished difference between one-target and two-target trials. In addition, we continued to examine whether both targets sharing the same cut-off side and potential response modulates performance in two-target discrimination trials.

Methods

Participants

Fifteen participants (9 female, mean age = 19.65) from the Brown University community volunteered to take part in this experiment for one hour in exchange for course credit or monetary compensation. All participants were right handed and had normal or corrected to normal vision and normal color vision. They were naïve to the goals of the experiment. The protocol was approved by the Brown University Institutional Review Board.

Apparatus

The same apparatus was used as in Experiment 1.

Stimuli and procedure

The stimulus and task procedure were the same as in the discrimination task of Experiment 1 except for the following. On each trial the number of distractors varied randomly. With equal probability, one target was presented with 2, 3, 5, 10, or 14 distractors and two targets were presented with either 3, 4, 6, 10, or 13 distractors. Figure 2A shows this manipulation equated the targets to distractors ratio on a subset of one-target and two-target trials. Specifically, targets to distractors ratios of 1:2, 1:3, and 1:5 were present during both one-target and two-target conditions, which consisted of displays containing one target with 2, 3, or 5 distractors (Figure 2A, top row) or two targets with 4, 6, or 10 distractors (Figure 2A, bottom row). Stimulus position was randomized under the following constraints: 1) stimuli had to be within a 10° by 10° invisible square surrounding the center of the screen, 2) stimuli could not appear within 1.0° of each other, 3) no stimuli were presented within 1.5° of the vertical midline of the display. When two targets were present the distance between them was always 5°. If a participant blinked or moved their eyes further than 1.25° from the cross the trial was discarded and replaced later in the block. Participants completed six blocks (90 trials/block) following a practice block. One participant completed only five blocks due to time constraints.

Data Analysis

For the comparison between one-target and two-target trials, only trials where the targets to distractors ratio was matched (1:2, 1:3 and 1:5; Figure 2A) were included. Using the same exclusion criteria as in Experiment 1, an average of 1.1% ± 0.1% of one-target trials and 1.2% ± 0.2% of two-target trials per subject were excluded from this analysis. When comparing trials where the target shapes and potential responses were identical (T_{same}) to when they were opposite ($T_{different}$), trials from all numbers of stimuli used were included. Using the same exclusion criteria as in Experiment 1, an average of 1.3% ± 0.2% of T_{same} trials and 1.1% ± 0.1% of $T_{different}$ trials per subject were excluded from analysis.

Results and Discussion

Effect of perceptual grouping: one vs. two target discrimination

We first assessed the effects of the number of targets and perceptual grouping on accuracy. $T_{different}$ trials were not included for the accuracy analysis as in Experiment 1. We did not observe an overall difference between one-target and T_{same} trials ($F_{1,14} = 0.05$, $p > 0.8$, $\eta^2 < 0.01$). However, the manipulation of targets to distractors ratio significantly affected accuracy ($F_{2,14} = 4.51$, $p < 0.05$, $\eta^2 = 0.03$): 92.7% ± 1.0% (1:2), 95.1% ± 1.1% (1:3), and 95.1% ± 0.9% (1:5). There was no significant interaction between number of targets and targets to distractors ratio ($F_{2,14} = 1.33$, $p > 0.1$, $\eta^2 = 0.01$). Altogether, these results suggest that discrimination accuracy increases as perceptual grouping gets stronger, but is not affected by the number of targets when perceptual grouping is matched.

We next compared reaction times in the one-target and two-target conditions. As Figure 2B demonstrates, reaction time decreased as the targets to distractors ratio decreased from 1:2 to 1:5. This result was consistent with prior studies demonstrating decreasing reaction times as the number of homogenous distractors increase (e.g., Duncan & Humphreys, 1989; Bravo & Nakayama, 1992; Song & Nakayama, 2006; Song et al., 2008). This decrease was confirmed by a significant main effect of targets to distractors ratio ($F_{2,14} = 7.18$, $p < 0.005$, $\eta^2 = 0.05$) when we conducted a two-way repeated measures ANOVA with factors number of targets (one vs. two) and targets to distractors ratio (1:2, 1:3, and 1:5). However, we did not observe a significant difference between the one-target (blue markers) and two-target conditions (purple markers; $F_{2,14} = 2.53$, $p > 0.1$, $\eta^2 < 0.01$) and no interaction with the targets to distractors ratio ($F_{2,14} = 2.08$, $p > 0.1$, $\eta^2 < 0.01$). These results suggest that when perceptual grouping was matched between one-target and two-target trials, reaction time was similar.

Effect of same or different targets on two-target discrimination

Overall accuracy for the T_{same} condition was 93.9% ± 1%. Next, we compared reaction time between the T_{same} and $T_{different}$ conditions. We analyzed performance at each total number of stimuli used during the two-target conditions because perceptual grouping was always equated between T_{same} and $T_{different}$ trials. Figure 2C shows that T_{same} trials (overall mean: 678 ± 13 ms, dark purple markers) are overall faster than $T_{different}$ trials (718 ± 16 ms, pink markers) across each number of stimuli presented ($F_{1,14} = 65.1$, $p < 0.001$, $\eta^2 = 0.09$). Furthermore, we also confirmed that increasing perceptual grouping facilitated search, as indicated by the decreasing reaction times for increasing total number of stimuli shown ($F_{4,14} = 17.33$, $p < 0.01$, $\eta^2 = 0.13$), which is consistent with prior research (e.g., Duncan & Humphreys, 1989; Bravo & Nakayama, 1992; Song & Nakayama, 2006). There was no significant interaction ($F_{4,14} = 1.96$, $p > 0.1$, $\eta^2 = 0.02$). Taken together, these results suggest slower reaction times on two-target trials when the target shapes and responses are different compared to when they are the same.

To summarize, Experiment 2 suggested that unmatched perceptual grouping between one-target and two-target trials in part contributed to the longer reaction times for two-target trials during discrimination in Experiment 1. In addition, we also demonstrated in two-target trials that when targets differed in shape and were thus associated with different potential responses ($T_{different}$, pink markers in Figure 2C), performance was slower than when target shapes and potential responses were the same (T_{same}, dark purple markers). Similar to our results, Fournier and Eriksen (1990) also reported that when discriminating the identity of a single target, the presence of two pre-defined targets associated with different responses (e.g., the left lever for an 'O' vs. the right lever for an 'X') lead to slower reaction times compared to when two identical targets were simultaneously presented. They reasoned this result occurred because both potential responses were activated, causing a competition between responses that had to be resolved before an appropriate response was executed (e.g., Eriksen & Schultz, 1979; Eriksen & Eriksen, 1979; Gratton, et al., 1988). While response competition could have resulted in slower reaction times in $T_{different}$ than T_{same} trials, we are not able to completely separate out the effect of response and target perceptual features (e.g., cut-off side). This is because the cut-off side of a target (top or bottom corner) determined the potential response to each target (press top or bottom button). Thus, in Experiment 3, we assessed the relative contributions of competition at the level of perceptual features and responses on two-target discrimination by dissociating these two aspects.

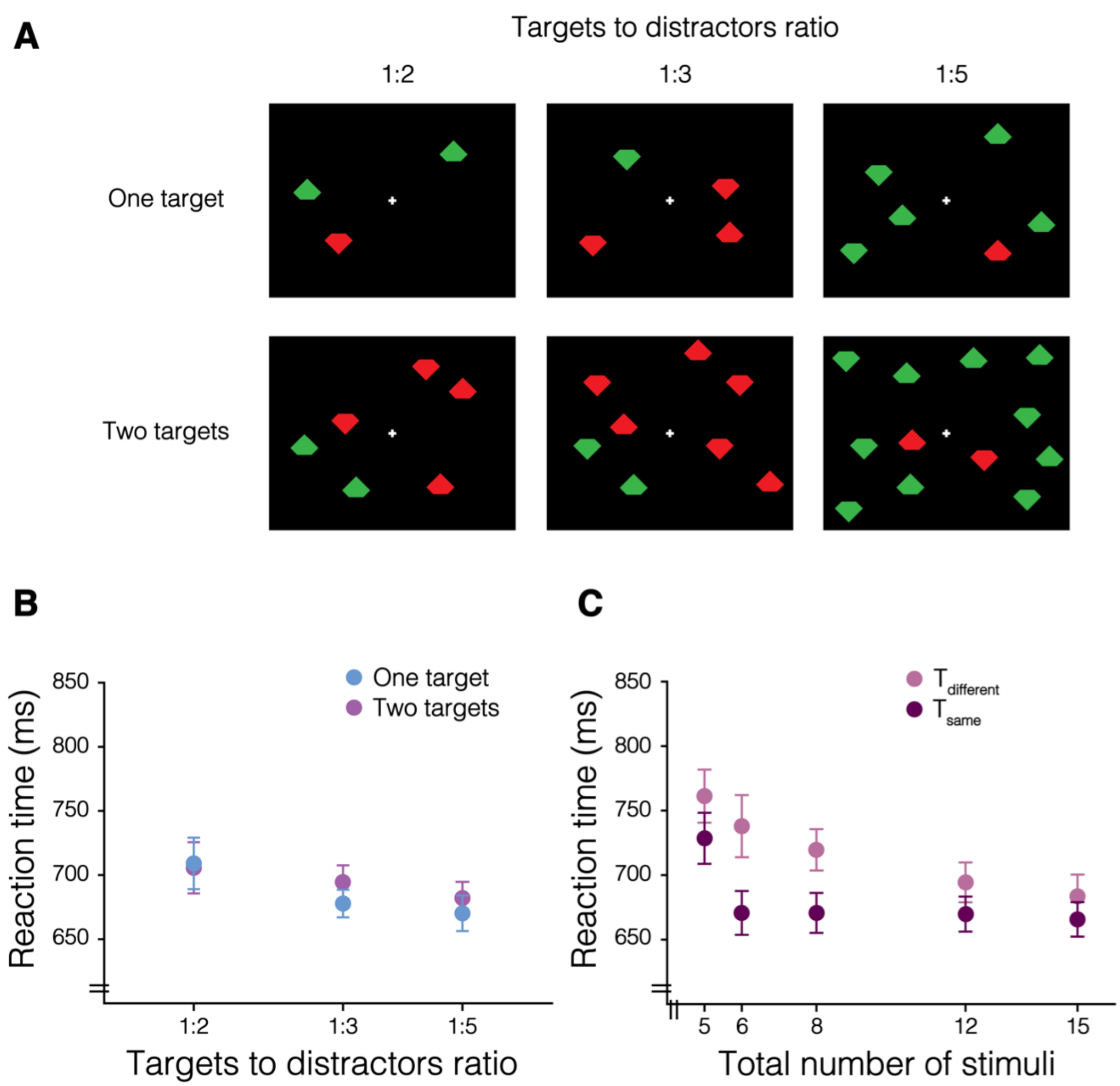

Figure 2. Task and results of Experiment 2. A. Representative displays for equated targets to distractors ratios. Participants reported whether the top or bottom corner was cut-off from one odd-colored target. Either one (top row) or two (bottom row) targets were presented on each trial. On two-target trials, each target shape was randomly selected, resulting in trials where targets were identical (T_{same}) or opposite ($T_{different}$). We manipulated the number of distractors to equate the targets to distractors ratio between one-target and two-target trials on a subset of trials. In each column here, we present example displays for each matched targets to distractors

ratio, 1:2 (left), 1:3 (middle), and 1:5 (right). **B. Mean reaction time as a function of targets to distractors ratio.** One-target trials are presented in blue and two-target trials are presented in purple. Reaction time did not differ between one-target and two-target trials when the targets to distractors ratio was equated. **C. Mean reaction time in the two-target trials.** Reaction time differed depending on whether targets were identical (T_{same}, pink) or opposite ($T_{different}$, dark purple). Error bars represent the between-participants standard error of the mean (s.e.m.).

Experiment 3: Does perceptual or response competition between targets modulate two-target discrimination performance?

In Experiments 1 and 2, two types of two-target trials were included: 1) two identical targets (T_{same}), which shared the same shape (S_{same}) and response (R_{same}) or 2) two different targets ($T_{different}$), which had different shapes ($S_{different}$) associated with different responses ($R_{different}$). In order to determine the relative contributions of perceptual and response competition in modulating two-target discrimination performance, we introduced a new two-target trial type, where both targets had different shapes ($S_{different}$) but were associated with the same response (R_{same}). Thus, we included the three types: 1) same shape-same response (S_{same} - R_{same}), 2) different shape-different response ($S_{different}$ - $R_{different}$), and 3) different shape-same response ($S_{different}$ - R_{same}). We reasoned that comparing performance in the new condition ($S_{different}$ - R_{same}) with the other two (S_{same} - R_{same} and $S_{different}$ - $R_{different}$) would provide further insight into how perceptual and/or response competition affected performance in two-target trials. The perceptual competition hypothesis would predict $S_{different}$ - R_{same} is slower than S_{same} - R_{same} while comparable in performance with $S_{different}$ - $R_{different}$ because different shapes should incur competition relative to the same shape condition. However, the response competition hypothesis would predict $S_{different}$ - R_{same} is faster than $S_{different}$ - $R_{different}$ while comparable in performance to S_{same} - R_{same} because different responses should incur competition relative to the two same response conditions.

Methods

Participants

Nineteen participants (12 female, mean age = 21) from the Brown University community volunteered to take part in this experiment for one hour in exchange for course credit or monetary compensation. All participants were right handed and had normal or corrected to normal vision and normal color vision. They were naïve to the goals of the experiment. The protocol was approved by the Brown University Institutional Review Board.

Apparatus

The same apparatus was used as in Experiments 1 and 2.

Stimuli and procedure

The stimuli and task procedure were the same as in Experiment 2 except for the following. Because our primary focus was comparisons among the two-target trials and not between one vs. two targets, we fixed the total of stimuli to six, in which either one or two targets were included. We modified the stimuli used in Experiments 1 and 2 by rotating them 45º (Figure 3A). Thus, for each stimulus, either the top-left, top-right, bottom-left, or bottom-right corner could be cut-off. The discrimination response remained the same as in Experiments 1 and 2, requiring participants to respond to a 'top' or 'bottom' cut-off corner regardless of whether it was cut-off from the left or right side of the target. Target shapes varied in whether their shapes and potential responses were the same or different, resulting in three conditions (Figure 3A): S_{same} - R_{same}, $S_{different}$ - R_{same} and $S_{different}$ - $R_{different}$. In the S_{same} - R_{same} condition, target shapes were always the same (e.g., top right and top right cut-off), that corresponded to the same response ('top', Figure 3A, left). In the $S_{different}$ - R_{same} condition, both targets had different shapes (e.g., top left vs. top right cut-off) that corresponded to the same potential response ('top', Figure 3A, middle). Finally, in the $S_{different}$ - $R_{different}$ condition, each target had a different shape (e.g., bottom right vs. top right cut-off) that corresponded to a different response ('top' and 'bottom', Figure 3A, right).

Each two-target condition occurred an equal number of times in each block. During two-target trials, a distractor with each of the four unique shapes were presented on every trial. For one-target trials, the fifth distractor was selected to be each possible shape an equal number of times within a block. Participants completed three blocks each after a block of practice. Within each block, one-target was presented on 32 trials (47%) and two targets were presented on 36 trials (53%).

Data Analysis

One participant was excluded from analysis because of poor performance. For the remaining 18 participants we used the same exclusion criteria for each trial as in the previous experiments. This resulted in a mean of 1.1% ± 0.2% of one-target trials, and 1.1% ± 0.4% , 0.8% ± 0.3%, and 0.6% ± 0.3% of S_{same} - R_{same}, $S_{different}$ - R_{same}, and $S_{different}$ - $R_{different}$ trials excluded from analysis. During analysis, subsequent pairwise comparisons were Bonferroni corrected.

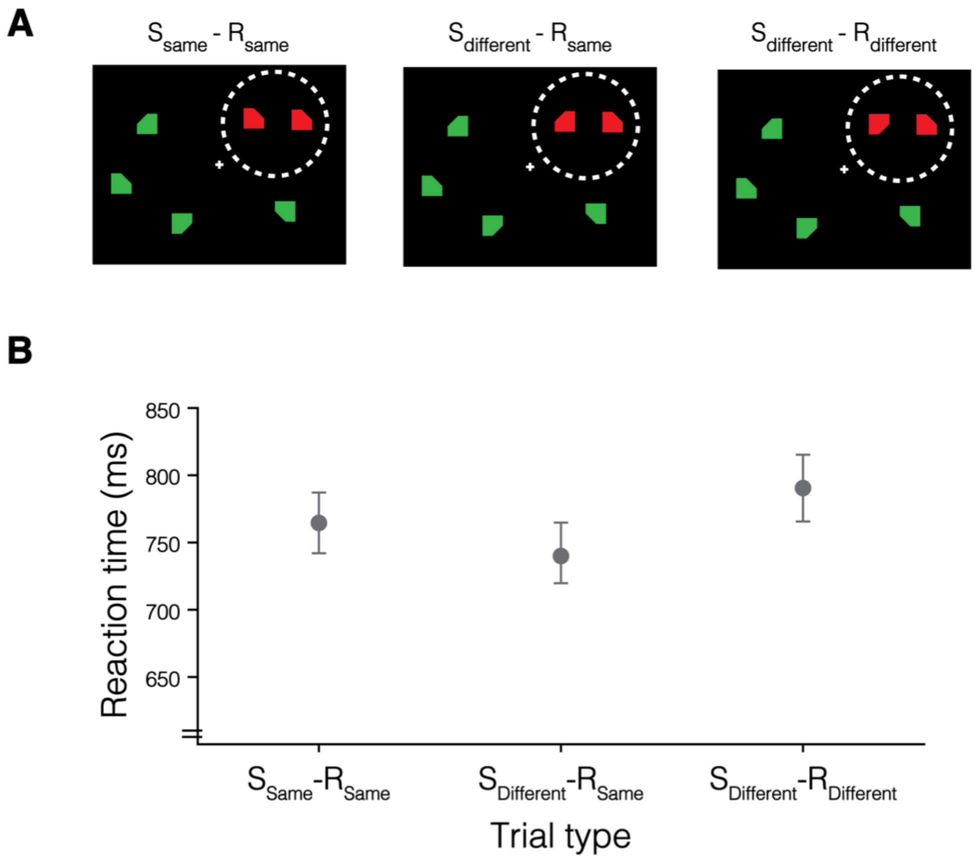

Figure 3. Task and results of Experiment 3. A. Representative displays. Participants reported whether the top or bottom corner was cut-off from one odd-colored target, regardless of whether it was cut-off from the left or right side. Either one or two targets were presented on each trial. On two-target trials, target shapes were randomly selected to create three trial types in combination of whether the shape (S) or response (R) between the two targets were the same or different: S_{same} - R_{same}, $S_{different}$ - R_{same} or $S_{different}$ - $R_{different}$. First, S_{same} - R_{same} refers to trials when identical targets were presented that were associated with the same response (left).

Second, $S_{different}$ - R_{same} refers to trials when targets had different cut-off corners that were associated with the same response (middle). Finally, $S_{different}$ - $R_{different}$ refers to trials when targets had different cut-off corners that were associated with the opposite responses (right). Both targets are highlighted by a dashed white line for display purposes only that was not presented in the experiment. **B. Mean reaction time for the three trial types.** In accord with the response competition hypothesis, $S_{different}$ - R_{same} (middle) is faster than $S_{different}$ - $R_{different}$ (right), while comparable in performance to S_{same} - R_{same} (left). Error bars represent the between-participants standard error of the mean (s.e.m.).

Results and Discussion

We first assessed how accuracy varied across conditions. $S_{different}$ - $R_{different}$ trials were dropped from the accuracy analysis because participants could not be wrong. Accuracy between the one-target (94.9% ± 0.8%), S_{same} - R_{same} (92.3% ± 1.2%), and $S_{different}$ - R_{same} (90.1% ± 1.7%) conditions differed significantly ($F_{2,17} = 9.40$, $p < 0.001$, $\eta^2 = 0.12$). Pairwise comparisons revealed percent correct was higher for the one-target trials than both the S_{same} - R_{same} trials ($t_{17} = 2.85$, $p < 0.05$, $d = 0.95$) and the $S_{different}$ - R_{same} trials ($t_{17} = 4.00$, $p < 0.005$, $d = 1.34$). However, the S_{same} - R_{same} condition did not differ significantly from the $S_{different}$ - R_{same} condition ($t_{17} = 1.83$, $p > 0.1$, $d = 0.62$).

We next examined whether reaction time differed between one-target and two-target trials. The average reaction time was slower for two-target relative to one-target trials ($t_{17} = 4.81$, $p < 0.001$, $d = 1.60$). This is consistent with the results of Experiment 1, where the total number of stimuli was kept constant at six as in this experiment. The critical comparison was how the $S_{different}$ - R_{same} condition differed significantly from the S_{same} - R_{same} and $S_{different}$ - $R_{different}$ conditions. We reasoned that response competition would result in faster reaction times in the $S_{different}$ - R_{same} condition, where the response is the same, than in the $S_{different}$ - $R_{different}$ condition, where the response is different, along with comparable performance to the S_{same} - R_{same} condition. In contrast, perceptual competition would result in slower reaction times in the $S_{different}$ - R_{same} condition, where the shapes are different, than in the S_{same} - R_{same} condition, where the shapes are the same, and comparable performance to the $S_{different}$ - $R_{different}$ condition.

Figure 3B depicts mean reaction time for each two-target trial type. In accord with the predictions of a response competition, we observed that reaction time in the $S_{different}$ - R_{same} condition was faster than the $S_{different}$ - $R_{different}$ condition, while similar to the S_{same} - R_{same} condition. An ANOVA revealed a significant main effect of trial type ($F_{2,17} = 12.36$, $p < 0.001$, $\eta^2 = 0.05$). Pairwise comparisons revealed that it was driven by faster reaction times for $S_{different}$ - R_{same} (middle) relative to the $S_{different}$ - $R_{different}$ condition (right; $t_{17} = 6.43$, $p < 0.005$, $d = 2.14$), with no significant difference between the $S_{different}$ - R_{same} (middle) and S_{same} - R_{same} condition (left; $t_{17} = 2.24$, $p > 0.05$, $d = 0.75$) after correction for multiple comparisons. The t-test comparing the S_{same} - R_{same} condition and the $S_{different}$ - $R_{different}$ condition ($t_{17} = 2.29$, $p > 0.05$, $d = 0.76$) was not significant.

General Discussion

Previous studies have investigated visual attention by including multiple targets during visual search tasks. These studies have generally focused on whether multiple targets are processed serially or in parallel (Pashler, 1987), whether search is self-terminating or exhaustive (Townshend, 1972, 1984; van der Heijden, 1975; van der Heijden, et al., 1974), as well as how visual information about multiple targets may be combined after attentional selection (e.g., in a purely parallel or a coactive manner; Fournier & Eriksen, 1990; Miller, 1982; van der Heijden, et al., 1984). We investigated whether distributed or focused attention during search modulates how multiple targets influence performance. To do so, we employed variants of a pop-out search task that are known to possess different attentional requirements. Pop-out detection is thought to suffice with distributed attention across a wide range of the visual field, while pop-out discrimination requires focused attention to a stimulus to resolve a perceptual feature (Nakayama, 1990; Bravo & Nakayama, 1992; Nakayama & Joseph, 1998; McPeek, et al., 1999; Song & Nakayama, 2006).

First, we observed that oddity target detection reaction times were faster when two targets were present compared to one target. The allocation of distributed attention during detection has been proposed to result in a representation of the visual field that is compared against templates held in memory associated with the presence or absence of a target (Nakayama, 1990; Bravo & Nakayama, 1992; Nakayama & Joseph, 1998). We conjecture that while attention is distributed, the greater intensity of target present signal for two targets compared to one facilitates detection by speeding up the template comparison process (Miller, 1982; Mordkoff & Yantis, 1993; Zehetleitner, et al., 2009).

In our task, targets were defined by being an odd-color, and target and distractor color was randomized on each trial. This task design requires the use of salient perceptual differences between targets and distractors to detect a target, rather than a search strategy that allows one to search for a specific feature. Contrary to our design, a series of studies by Krummenacher and colleagues investigated the effects of multiple targets on oddity target detection when target features were pre-specified to participants, thereby allowing the use of target feature information to bias search (Krummenacher, et al., 2001, 2002, 2014; Töllner, et al., 2011). In their tasks, targets were defined in two feature dimensions (e.g., a red stimulus and a right oriented line) and a multiple target trial would consist of both feature dimensions (e.g., a red right-oriented line). The authors demonstrated faster reaction times when multiple targets were present compared to when either target was present alone due to an intensified target-present signal (Krummenacher, et al., 2001, 2002). Even with the differences in task, the common result found in our study and by Krummenacher and colleagues suggests that multiple salient targets facilitate detection regardless of foreknowledge about the target defining feature.

Second, when participants performed a pop-out discrimination task, we initially observed that reaction time was slower when two targets were present relative to one. In subsequent experiments, we further examined what factors contributed to this slowed reaction time during two-target discrimination, which differed from what we observed during detection. We found that matching the perceptual grouping efficiency between one-target and two-target displays reduced the reaction time cost for two targets, suggesting that perceptual grouping modulates the impact of multiple targets. It has been proposed that perceptual grouping efficiency modulates pop-out discrimination because of the need to allocate focused attention to a target, but not pop-out detection (Bravo & Nakayama, 1992; Julesz, 1986; Koch & Ullman, 1985; McPeek et al., 1999; Song & Nakayama, 2006). This may partly explain the asymmetry in the effects of multiple targets across tasks that we observed in this study.

We also demonstrated that performance on pop-out discrimination with two targets was modulated by the competition of potential responses associated with each target rather than perceptual features. Reaction time when either target was associated with opposite responses was slower than when the responses were the same, regardless of whether the target shapes matched or not. This pattern of results suggests that both responses associated with either target were activated and that interference driven by the opposing nature of the responses (press ‘top’ or ‘bottom’) incurred slowed reaction times. Many studies suggest that simultaneously active responses can compete with each other, which causes conflict that must be resolved prior to one response being executed (Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979; Gratton, et al., 1988; Fournier & Eriksen, 1990). Our results suggest that such a competition may arise during pop-out discrimination when multiple targets differ in their potential responses.

This response competition that we observed is also consistent with the notion of “event files” (Hommel, 2004, 2005). According to Hommel (2004, 2005), when a participant encounters a perceptual event and responds with a specific action, a transient “event file” is created in which a representation of the perceptual event, task context, and associated action are bound. These files can be retrieved during future encounters with that same perceptual event and task context, thereby reducing the demand on limited cognitive resources required for action selection. Perhaps, in our task, the presence of two targets with different perceptual features associated with different responses elicited response competition by simultaneously activating both event files associated with a target missing a top and bottom corner, thereby priming both responses.

Classic theories of visual attention propose that the feature information of a target is available only after attention is allocated to the target (Eriksen & St. James, 1986; Nakayama & Joseph, 1998; Treisman & Gelade, 1980; Wolfe, 1994; Wolfe, 2007). It follows that a response predicated on a target feature, such as during the discrimination tasks in our study, requires the feature information that is available only after the target is attended. Thus, according to these theories our finding that target responses modulate two-target pop-out discrimination performance suggests that both targets were attended in this task. There is considerable evidence that attention may be split between multiple stimuli (Cavanagh & Alvarez, 2005; McMains &

Sommers, 2004; Pylyshyn & Storm, 1988), including during visual search (Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016). Given the highly salient nature of the targets used in our pop-out task, it is plausible that attention may have been directed to both targets, either inadvertently or as part of a strategy that participants employed. To summarize, our study has provided further insight into possible factors that modulate the efficiency of visual search when multiple targets are simultaneously present and either broadly distributed or focused attention is required.

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References

Akyürek, E. G., & Schubö, A. (2013). The electrophysiological locus of the redundant target effect on visual discrimination in a dual singleton search task. *Brain Research*, *1537*, 180–190. http://doi.org/10.1016/j.brainres.2013.09.014

Atkinson, J., & Braddick, O. J. (1989). "Where" and "what" in visual search. *Perception*, *18*(2), 181–189. http://doi.org/10.1068/p180181

Bacon, W. F., & Egeth, H. E. (1991). Local Processes in Preattentive Feature Detection. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(1), 77–90. http://dx.doi.org/10.1037/0096-1523.17.1.77

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics*, *55*(5), 485–496. http://doi.org/10.3758/BF03205306

Baddeley, A. D., & Ecob, R. J. (1973). Reaction time and Short-term Memory: Implications of Repetition Effects for the High-speed Exhaustive Scan Hypothesis. *Quarterly Journal of Experimental Psychology*, *25*(2), 229-240. https://doi.org/10.1080/14640747308400342

Bjork, E. L. & Estes, W. K. (1971) Detection and placement of redundant signal elements in tachistoscopic displays of letters. *Perception & Psychophysics, 9*(5), 439-442. https://doi.org/10.3758/BF03210248

Bravo, M. J., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception and Psychophysics*, *51*(5), 465–472. https://doi.org/10.3758/BF0321164

Bundesen, C., & Pedersen, L. F. (1983). Color segregation and visual search. *Perception and Psychophysics*, *33*(5), 487-493. https://doi.org/10.3758/BF03202901

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. Trends in *Cognitive Sciences, 9*(7), 349–354. https://doi.org/10.1016/j.tics.2005.05.009

Cohen, J. (1988). Statistical Power Analysis for the Behavioral Sciences. New York, NY: Routledge Academic. https://doi.org/10.1016/C2013-0-10517-X

Duncan, J., & Humphreys, G. W. (1989). Visual Search and Stimulus Similarity. *Psychological Review*, *96*(3), 433–458. http://dx.doi.org/10.1037/0033-295X.96.3.433

Egeth, H. E., & Mordkoff, J. T. (1991). Redundancy gain revisited: Evidence for parallel processing of separable dimensions. In G. R. Lockhead & J. R. Pomerantz (Eds.), *The perception of structure: Essays in honor of Wendell R. Garner* (pp. 131-143). Washington, DC: American Psychological Association. http://dx.doi.org/10.1037/10101-007

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*(2), 193–198. http://doi.org/10.1016/j.cub.2013.12.001

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. http://doi.org/10.3758/BF03203267

Eriksen, C. W., & Eriksen, B. A. (1979). Target redundancy in visual search: Do repetitions of target within the display impair processing? *Perception & Psychophysics*, *26*(3), 356–370. https://doi.org/10.3758/BF03199869

Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, *25*(4), 249–263. https://doi.org/10.3758/BF03198804

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, *40*(4), 225–240. https://doi.org/10.3758/BF03211502

Estes, W. K., & Taylor, H. A. (1966). Visual detection in relation to display size and redundancy of critical elements I. *Perception & Psychophysics*, *1*(1), 9–16. http://doi.org/10.3758/BF03207814

Farmer, E. W., & Taylor, R. M. (1980). Visual search through color displays: Effects of target-background similarity and background uniformity. *Perception and Psychophysics*, *27*(3), 267-272. https://doi.org/10.3758/BF03204265

Folk, C. L., & Egeth, H. (1989). Does the identification of simple features require serial processing? *Journal of Experimental Psychology: Human Perception and Performance*, *15*(1), 97–110. http://dx.doi.org/10.1037/0096-1523.15.1.97

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(4), 1030–1044. http://dx.doi.org/10.1037/0096-1523.18.4.1030

Fournier, L. R., & Eriksen, C. W. (1990). Coactivation in the Perception of Redundant Targets. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(3), 538–550. http://dx.doi.org/10.1037/0096-1523.16.3.538

Gratton, G., Coles, M. G. H., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Pre- and Poststimulus Activation of Response Channels: A Psychophysiological Analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(3), 331–344. http://doi.org/10.1037/0096-1523.14.3.331

Green, M. (1992). Visual search: Detection, identification, and localization. *Perception, 21*(6), 765–777. https://doi.org/10.1068/p210765

Grubert, A., & Eimer, M. (2015). Rapid parallel attentional target selection in single-color and multiple-color visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(1), 86–101. http://dx.doi.org/10.1037/xhp0000019

Grubert, A., & Eimer, M. (2016). Rapid attentional selection processes operate independently and in parallel for multiple targets. *Biological Psychology*, *121*, 99–108. https://doi.org/10.1016/j.biopsycho.2016.10.012

Holmgren, J. E., Juola, J. F., & Atkinson, R. C. (1974). Response latency in visual search with redundancy in the visual display. *Perception & Psychophysics*, *16*(1), 123–128. http://doi.org/10.3758/BF03203264

Hommel, B. (2004). Event files: feature binding in and across perception and action. *Trends in Neurosciences*, *8*(11), 494–500. http://doi.org/10.1016/j.tics.2004.08.007

Hommel, B. (2005). Perception in action: multiple roles of sensory information in action control. *Cognitive Processing*, *6*(1), 3–14. https://doi.org/10.1007/s10339-004-0040-0

Johnston, J. C., & Pashler, H. (1990). Close Binding of Identity and Location in Visual Feature Perception. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(4), 843–856. http://doi.org/10.1037/0096-1523.16.4.843

Joseph, J. S., Chun, M. M., & Nakayama, K. (1997). Attentional requirements in a ‘preattentive’ feature search task. *Nature*, *387*, 805–807. http://doi.org/10.1038/42940

Julesz, B. (1981). Textons, the elements of texture perception, and their interactions. *Nature*, *290*, 91-97. https://doi.org/10.1038/290091a0

Julesz, B. (1986). Texton gradients: The texton theory revisited. *Biological Cybernetics*, *54*(4–5), 245–251. http://doi.org/10.1007/BF00318420

Koch, C. & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. In L. M. Vaina (Ed.), *Matters of Intelligence: Conceptual Structures in Cognitive Neuroscience*. (pp. 115-141). Dordrecht, Holland: D. Reidel. https://doi.org/10.1007/978-94-009-3833-5_5

Kristjánsson, Á., Mackeben, M., & Nakayama, K. (2001). Rapid, object-based learning in the deployment of transient attention. *Perception*, *30*(11), 1375–1387. http://doi.org/10.1068/p3251

Krummenacher, J., Grubert, A., Töllner, T., & Müller, H. J. (2014). Salience-based integration of redundant signals in visual pop-out search: Evidence from behavioral and electrophysiological measures. *Journal of Vision*, *14*(3), 1–17. http://doi.org/10.1167/14.3.26

Krummenacher, J., Müller, H. J., & Heller, D. (2001). Visual search for dimensionally redundant pop-out targets: Evidence for parallel-coactive processing of dimensions. *Perception & Psychophysics*, *63*(5), 901–917. http://doi.org/10.1037//0096-1523.28.6.1303

Krummenacher, J., Müller, H. J., & Heller, D. (2002). Visual search for dimensionally redundant pop-out targets: Parallel-coactive processing of dimensions is location specific. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(6), 1303–1322. http://doi.org/10.1037//0096-1523.28.6.1303

Lakens, D. (2013) Calculating and reporting effect sizes to facilitate cumulative science; a practical primer for *t*-tests and ANOVAs. *Frontiers in Psychology*, *4*(863), 1-12. https://doi.org/10.3389/fpsyg.2013.00863

McMains, S. A., & Somers, D. C. (2004). Multiple spotlights of attentional selection in human visual cortex. *Neuron*, *42*(4), 677–686. http://doi.org/S0896627304002636

McPeek, R. M., Maljkovic, V., & Nakayama, K. (1999). Saccades require focal attention and are facilitated by a short-term memory system. *Vision Research*, *39*(8), 1555–1566. https://doi.org/10.1016/S0042-6989(98)00228-4

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, *14*(2), 247–279. http://doi.org/10.1016/0010-0285(82)90010-X

Mordkoff, J. T., & Yantis, S. (1993). Dividing attention between color and shape: Evidence of coactivation. *Perception & Psychophysics*, *53*(4), 357–366. http://doi.org/10.3758/BF03206778

Nakayama, K. (1990). The iconic bottleneck and the tenuous link between early visual processing and perception. In C. Blakemore (Ed.), *Vision: Coding and Efficiency* (pp. 411–422). Cambridge and New York: Cambridge University Press.

Nakayama, K., & Joseph, J. S. (1998). Attention, pattern recognition and pop-out in visual search. In R. Parasuraman (Ed.), *The Attentive Brain* (pp. 279–298). Cambridge: MIT press.

Nakayama, K., & Mackeben, M. (1989). Sustained and Transient Components of Focal Visual Attention. *Vision Research*, *29*(11), 1631–1647. https://doi.org/10.1016/0042-6989(89)90144-2

Nakayama, K. & Martini, P. (2011) Situating visual search. *Vision Research*, *51*(13), 1526-1537. https://doi.org/10.1016/j.visres.2010.09.003

Pashler, H. (1987). Detecting conjunctions of color and form: reassessing the serial search hypothesis. *Perception & Psychophysics*, *41*(3), 191–201. http://doi.org/10.3758/BF03208218

Pylyshyn, Z.W., & Storm, R.W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3*(3), 1–19. http://dx.doi.org/10.1163/156856888X00122

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, *24*, 574–590. http://doi.org/10.1111/j.2164-0947.1962.tb01433.x

Sagi, D., & Julesz, B. (1985A). Detection versus discrimination of visual orientation. *Perception*, *13*(5), 619–628. http://doi.org/10.1068/p130619

Sagi, D., & Julesz, B. (1985B). "Where" and "what" in vision. *Science*, *228*(4704), 1217–1219. http://doi.org/10.1126/science.4001937

Song, J.-H., & Nakayama, K. (2006). Role of focal attention on latencies and trajectories of visually guided manual pointing. *Journal of Vision*, *6*, 982–995. http://doi.org/10.1167/6.9.11

Song, J.-H., Takahashi, N., & McPeek, R. M. (2008). Target selection for visually guided reaching in macaque. *Journal of Neurophysiology*, *99*(1), 14–24. http://doi.org/10.1152/jn.01106.2007

Töllner, T., Zehetleitner, M., Krummenacher, J., & Müller, H. J. (2011). Perceptual basis of redundancy gains in visual pop out search. *Journal of Cognitive Neuroscience*, *23*(1), 137–50. http://doi.org/10.1162/jocn.2010.21422

Townsend, J. T., & Ashby, F. G. (1982). An experimental test of contemporary mathematical models of visual letter recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(6), 834-864. http://dx.doi.org/10.1037/0096-1523.8.6.834

Townsend, J. T. (1972). Some results concerning the identifiability of parallel and serial processes. *British Journal of Mathematical and Statistical Psychology*, *25*(2), 168-199. https://doi.org/10.1111/j.2044-8317.1972.tb00490.x

Treisman, A., Sykes, M., & Gelade, G. (1977) Selective attention and stimulus integration. In S. Dornic (Ed.), *Attention and performance VI* (pp. 333-361). Hillsdale, NJ: Lawrence Erlbaum.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, *95*(1), 15–48. http://doi.org/10.1037/0033-295X.95.1.15

Treisman, A., & Sato, S. (1990) Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance. 16*(3), 459-478. http://dx.doi.org/10.1037/0096-1523.16.3.459

Treisman, A. (1988). Features and Objects: The 14th Bartlett Memorial Lecture. *The Quarterly Journal of Experimental Psychology*, *40*(2), 201–237. https://doi.org/10.1080/02724988843000104

van der Heijden, A. H., & Menckenberg, H. W. (1974). Some evidence for a selfterminating process in simple visual search tasks. *Acta Psychologica, 38*(3), 169-181. http://dx.doi.org/10.1016/0001-6918(74)90032-8 van der Heijden, A. H. C., Schreuder, R., Maris, L., & Neerincx, M. (1984). Some evidence for correlated separate activation in a simple letter-detection task. *Perception & Psychophysics*, *36*(6), 577–585. http://doi.org/10.3758/BF03207519

van der Heijden, A. H. (1975). Some evidence for a limited capacity parallel self-terminating process in simple visual search tasks. *Acta Psychologica*, *39*(1), 21–41. http://doi.org/10.1016/0001-6918(75)90019-0

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–238. http://doi.org/10.3758/BF03200774

Wolfe, J. M. (2007). Guided Search 4.0: Current Progress With a Model of Visual Search. In W. D. Gray (Ed.), *Series on cognitive models and architectures: Integrated models of cognitive systems* (pp.99–119). New York: Oxford University Press.

Zehetleitner, M., Krummenacher, J., & Müller, H. J. (2009). The detection of feature singletons defined in two dimensions is based on salience summation, rather than on serial exhaustive or interactive race architectures. *Attention, Perception & Psychophysics*, *71*(8), 1739–1759. http://doi.org/10.3758/APP