Target detection and discrimination in pop-out visual search with two targets

James P. Wilmott*, Mukesh Makwana* & Joo-Hyun Song

Department of Cognitive, Linguistic & Psychological Sciences, Brown University, RI 02912

* James P. Wilmott and Mukesh Makwana contributed equally and are co-first author

Page count: 44

Figure count: 3

Keywords: attention, detection, discrimination, pop-out search, additional target

Correspondence to: Joo-Hyun Song

Department of Cognitive, Linguistics & Psychological Sciences

Box 1821

Brown University Providence, RI 02912-1821

Joo-hyun_song@brown.edu

Tel: 1-401-863-7666 (P)

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

Abstract

To successfully interact with objects in complex and crowded environments, we often perform visual search to detect or identify a relevant target (or targets) among distractors. Previous studies have reported a *redundancy gain* when two targets instead of one are presented in a simple target detection task. However, research is scant about the role of multiple targets in target discrimination tasks, especially in the context of visual search. Here, we address this question and investigate its underlying mechanisms in a pop-out search paradigm. In Experiment 1, we directly compared visual search performance for one or two targets for detection or discrimination tasks. We found that two targets led to a redundancy gain for detection, whereas it led to a *redundancy cost* for discrimination. To understand the basis for the redundancy cost observed in discrimination tasks for multiple targets, we further investigated the role of perceptual grouping (Experiment 2) and stimulus-response feature compatibility (Experiment 3). We determined that the strength of perceptual grouping among homogenous distractors was attenuated when two targets were present compared to one. We also found that response compatibility between two targets contributed more to the redundancy cost compared to perceptual compatibility. Taken together, our results show how pop-out search involving two targets is modulated by the level of feature processing, perceptual grouping, and compatibility of perceptual and response features.

Introduction

Everyday visual scenes are often complex and crowded, where many objects compete for visual attention and selection. To successfully interact in such environments, animals (including humans) often perform visual search to detect or identify relevant objects among distractors. 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). A typical visual search paradigm involves searching for one target (e.g., 'red' circle, letter 'T' or a 'tilted' bar) among many distractors (e.g., 'green' circles, letter 'Ls' or 'vertical' bars). Often, different parameters related to distractors are manipulated such as distractor set size, distractor homogeneity, and distractor similarity to the target (Calder-Travis & Ma, 2020; Palmer, 1994; Wolfe, 2020). However, in real life there exists situations where multiple copies of a target may be present, and sometimes these targets might contain conflicting information (Adamo et al., 2021; Won & Jiang, 2013). For instance, an animal might have to search for multiple predators approaching from different directions or in a social setting a human might have to look for a facial expression amongst other similar or different expressions in the crowd (Won & Jiang, 2013). Another example is in radiology, where detecting one target can interfere with the search for subsequent targets, a phenomenon known as satisfaction-of-search or subsequent-search-misses (Adamo et al., 2021). Previous studies have sought to understand how redundant target information (e.g., multiple targets or features) impacts visual search performance (Egeth & Mordkoff, 1991; Estes & Taylor, 1966; Holmgren, et al., 1974; Thornton & Gilden, 2007; van der Heiden, 1975).

Earlier studies investigated the role of redundant target information using either simple detection (i.e., reporting the presence or absence of a target) or Go/No-go tasks. When participants are required to simply detect a pre-defined target, responses are faster and more accurate when there are two targets compared to when there is only one target (e.g., Corballis, 2002; Fischer & Miller, 2008; Giray & Ulrich, 1993; Miller, 1982; Miniussi, Girelli & Marzi, 1998; Mordkoff & Yantis, 1991; Raab, 1962). This performance benefit is generally referred to as a *redundancy gain* (also known as *redundant target effects* or *redundant signal effects*) because the second target produces a gain in performance even though it is redundant. The term redundancy gain has also been used when the number of targets in the display remains the same but the number of target defining features are manipulated (e.g., targets are defined as being either a certain shape or a certain color). In such studies, visual search performance improves when a target consists of more than one target defining feature compared to only one feature (Krummenacher, et al., 2001, 2002; Miller, 1982). The two most popular categories of models proposed to explain redundancy gain are race models (Corballis, 1998; Raab, 1962; Reuter-Lorenz et al., 1995) and coactivation models (Miller, 1982; Ulrich, Miller, & Schröter, 2007). On one hand, independent parallel race models postulate that signals from multiple targets (or feature dimensions) are processed independently so that target detection is determined by the signal that wins the race, which is lower than the average time for any single target (see Raab, 1962; Mordkoff & Yantis, 1991,1993). In contrast, co-activation models propose that signals from each target or dimension are summated at a stage before the response and thereby reach the response threshold more quickly (Miller, 1982). However, the exact mechanisms underlying redundancy gain are still debated (Corballis, 1998; Fischer & Miller, 2008; Mordkoff & Yantis, 1991). For instance, Giray and Ulrich (1993) showed that participants were not only faster but

also responded with greater force when two targets were presented compared to one, supporting a motor coactivation hypothesis. An electroencephalographical study by Miniussi, Girelli, and Marzi (1998) revealed that peak latencies for event related potentials were earlier when two targets (bilateral) were presented compared to one target (unilateral), supporting a perceptual coactivation hypothesis. Furthermore, most of these models were used to explain redundancy gain in studies that primarily involved either target detection task without distractors or Go/NoGo task, wherein multiple targets had identical perceptual features and associated responses.

A redundancy gain has also been reported in feature singleton detection tasks wherein multiple feature dimensions are used to define a target (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 features (orientation and color) were faster than those including a target defined individually by either feature. 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). Redundancy gain has also been observed for detection of tumors in simulated X-ray images (Hebert et al., 2020). For instance, Hebert et al., (2020) showed that displaying multiple identical or similar images yields significantly lower false-negative rates. They suggested that the redundancy gain may reflect a combination of enhanced perception, an alteration in search procedure, and a change in the threshold for when to quit search.

Many of these previous studies demonstrating redundancy gains have primarily employed target detection tasks where both redundant target yield the same target present or absent

response. Much less is known about how redundant targets defined by one feature (e.g., color) interact during visual search when fine-detail discrimination (e.g., cut-off side of the target) is required for response. The present study aimed to examine whether the redundancy gain observed in detection tasks also occurs during discrimination tasks when one vs. two copies of a target are present.

Previous studies have demonstrated that while pop-out detection is thought to suffice with distributed attention across a wide range of the visual field, pop-out discrimination requires focused attention to a stimulus to resolve a perceptual feature. Consequently, pop-out search performance differs as a function of distractor number for detection compared to discrimination task (Bravo & Nakayama, 1992; Maljkovic & Nakayama, 1994; McPeek, et al., 1999; Nakayama, 1990; Song & Nakayama, 2006). For instance, Bravo and Nakayama (1992) revealed distinctive visual search patterns associated with target detection and discrimination. They presented an odd-colored diamond target among homogeneous colored distractors, where target and distractor colors were randomly switched from trial-to-trial. When participants were required to detect the presence or absence of a target, reaction times were relatively fast and did not vary with the number of distractors, 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. This diverging pattern of reaction times in detection and discrimination pop-out search tasks have been consistently reported in both humans and non-human primates (Kristjansson, et al., 2001; Nakayama & Mackeben, 1989; Song & Nakayama, 2006; Song, et al., 2008). 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). Here, we modified Bravo and Nakayama's paradigm to examine how varying the number of odd-colored targets (one vs. two) influences visual search in target detection and discrimination task.

In accord with prior work, we expected to observe a redundancy gain for two targets compared to one target during detection because more targets in the search display leads to faster detection (Giray & Ulrich, 1993; Krummenacher, et al., 2001; Miller, 1982; Miniussi, Girelli & Marzi, 1998; Mordkoff & Yantis, 1991; Raab, 1962). However, we expect that discrimination task performance may differ based on the perceptual and attentional requirements of feature discrimination (Bravo & Nakayama, 1992; Flowers & Garner, 1971; Garner & Flowers, 1969; Schopper et al., 2019) (Experiment 1), the strength of perceptual grouping (Experiment 2) and conflict between differential perceptual features or response activation associated with different targets (Experiment 3).

Experiment 1: How do two odd-colored targets affect visual detection and discrimination?

In Experiment 1, we examined how target detection and discrimination are impacted by the presence of two redundant odd-colored targets among homogenous distractors. Following Bravo and Nakayama (1992), we asked participants to perform both a detection task and a discrimination task. 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 in the context of redundancy gain including two targets has never been directly compared using the same display.

Methods

Participants

The sample size was predetermined on the basis of previous work examining redundancy gain (Grubert et al., 2011; Hebert et al., 2020; Krummenacher et al., 2001; Miniussi et al., 1998; Won & Jiang, 2013). The estimated power was greater than .95 with a sample size of 15.

Fifteen participants (7 female, mean age = 21 years old) 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. In parallel with previous studies investigating attentional constraints on search (Bravo & Nakayama, 1992; Song

& Nakayama, 2006; Song et al., 2008), we required participants to maintain fixation at a central fixation cross. It enables us, in turn, to minimize the impact of different eye movement strategies on visual search (e.g., serial vs. parallel) as well as to create more comparable contexts to examine differences between target detection and discrimination tasks.

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, the stimulus array with 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 note that this task is different from visual search tasks in subsequent-search-misses or satisfaction-of-search phenomenon where participants are expected to search all possible targets in the display (Adamo et al., 2021). 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. Reaction time was measured as the difference in time between the onset of the stimulus array and the subsequent press of the '2' or '8' key to report their response. When comparing reaction times, we excluded trials where the response was incorrect. We conducted repeated measure ANOVAs and applied Bonferroni correction for planned pairwise comparisons. Greenhouse-Geisser correction was applied whenever sphericity assumption was violated. Effect size was estimated using η^2_G and Cohen's d. η^2_G is known to provide more conservative and reliable estimates for within-subject design as in the present study than η^2 in which 0.01, 0.06 or 0.14 corresponds to a small, medium and large effect (Bakeman, 2005; Cohen,1988; Lakens, 2013; Olejnik, & Algina, 2003). 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 ($F_{1.19,16.68} = 20.16$, $p < .001$, $\eta^2_G = 0.379$) and pairwise comparisons between target-absent and one- target trials ($t_{14} = 5.04$, $p < .001$, $d = 1.3$) and target-absent and two- target trials ($t_{14} = 4.55$, $p < .001$, $d = 1.17$). However, one- target and two-target conditions did not significantly differ from each other after correction for multiple comparisons ($t_{14} = 2.31$, $p > .1$, $d = 0.6$). On two-target trials, the distance between targets was randomly chosen to be 3°, 5°, or 7°. There was no main effect of distances in accuracy ($F_{2,28} = 0.13$, $p = .8$, $\eta^2_G = 0.005$).

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 ($F_{1.18,16.52} = 45.24$, $p < .001$, $\eta^2_G = 0.168$). Further planned analysis indicated that reaction time on target-absent trials (gray) was slower than on one-target present trials (blue; $t_{14} = 5.44$, $p < .001$, $d = 1.4$) consistent with previous visual search studies (e.g., Treisman & Gelade, 1980; Bravo & Nakayama, 1992). Of interest was whether two targets (purple) facilitates or deteriorates visual search. We observed faster reaction time in the two-target trials compared to one-target trials (blue; $t_{14} = 4.65$, $p = .001$, $d = 1.20$). This result is 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; $t_{14} = 8.46$, $p < .001$, $d = 2.18$). On two-target trials, we observed a significant effect of distance ($F_{2,28} = 6.54$, $p = .005$, $\eta^2_G = 0.010$). This effect was driven by faster reaction times when targets were presented 7° apart (500 ± 14 ms) than 3° (512 ± 14 ms; $t_{14} = 3.37$, $p = .014$, $d = 0.872$). However, there was no significant difference between the 3° and 5° (511 ± 15 ms; $t_{14} = 0.121$, $p > .9$, $d = 0.03$), and between 5° and 7° ($t_{14} = 2.56$, $p = .067$, $d = 0.663$).

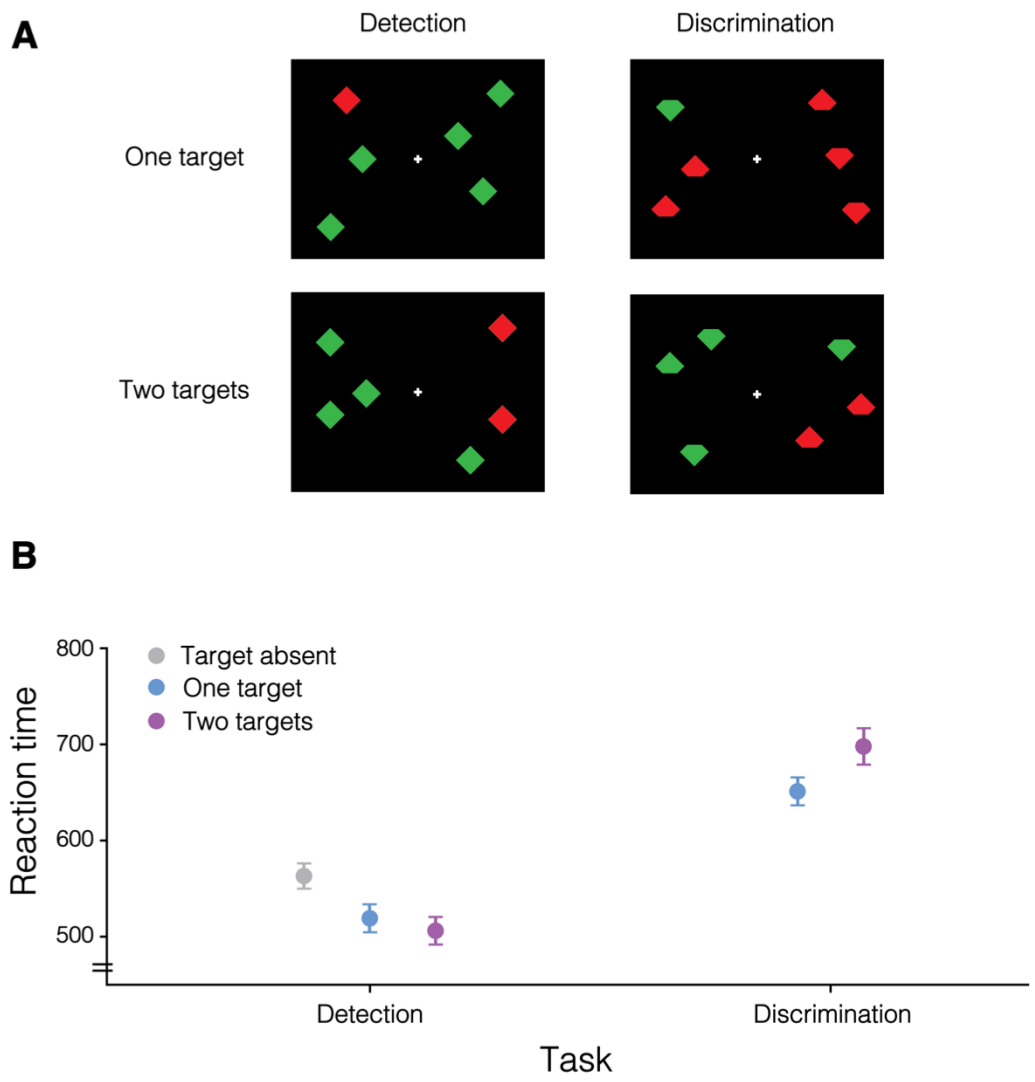

Figure 1. Tasks and results of Experiment 1. A. Representative displays. In both detection (left column) and discrimination (right column), one (top row) or two (bottom row) odd-colored targets were randomly presented among homogenously colored distractors. During detection, participants reported whether 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.).

Discrimination task

We compared accuracy in one-target trials with two-target trials in which both targets share the same cut-off side (T_{same}). We limited our analysis to these trials 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%; $t_{14} = 3.22$, $p = .006$, $d = 0.833$).

Figure 1B (right) shows the average reaction time for the one target and two target conditions in the discrimination task. Overall reaction time was slower in the two-target (purple; 696 ± 19 ms) than one-target condition (blue; 651 ± 15 ms), which was the opposite of what we observed in the detection task. To assess differences between conditions, we compared one-target against T_{same} and $T_{different}$ trials in two-target condition and observed a significant effect ($F_{1.43,20} = 16.26$, $p < .001$, $\eta^2_G = 0.147$). One-target trials were significantly faster than both $T_{different}$ trials (721 ± 24 ms; $t_{14} = 4.9$, $p < .001$, $d = 1.26$) and T_{same} trials (676 ± 15 ms; $t_{14} = 3.26$, $p = .017$, $d = 0.843$). For the two-target condition, one might think that the $T_{different}$ condition would 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 (676 ± 15 ms; $t_{14} = 3.169$, $p = .020$, $d = 0.818$).

We further assessed whether reaction time varied in two-target trials based on inter-target distance. To do so, we conducted an 3x2 repeated measures ANOVA with factors distance (3°, 5°, or 7°), and target type (T_{same} or $T_{different}$). While the main effect of target type was significant

($F_{1,14} = 8.9$, $p = .01$, $\eta^2_G = 0.059$), neither distance ($F_{2,28} = 2.15$, $p = .135$, $\eta^2_G = 0.013$) nor the interaction ($F_{2,28} = 0.37$, $p = .695$, $\eta^2_G = 0.002$) was significant.

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, resulting in a redundancy cost. In subsequent experiments, we further investigated what contributed to this inefficiency redundancy cost related during discrimination.

Here, 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 with one target have shown that as the number of homogenous distractors increases, the strength of perceptual grouping due to distractors 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 redundancy cost.

Experiment 2: Does perceptual grouping contribute to redundancy cost during discrimination?

Here, we examined whether the redundancy cost observed in Exp. 1 during target discrimination was led by weakened perceptual grouping during discrimination. Perceptual grouping is 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). Therefore, 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 during discrimination. For example, at a target 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.

Methods

Participants

Fifteen participants (9 female, mean age = 19.65 years old) 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°. In Experiment 1, we did not observe a significant effect of distance between targets in reaction time for two target trials during discrimination. Given that null effect, we affixed distance at 5 degrees as it was not a variable of interest. While the distance between targets was always the same, both the angular direction of the location of the second target relative to the first and the actual positions of both targets in the display were randomized. Moreover, participants were instructed to discriminate and report the shape of only one target, meaning that successful task performance did not require finding both targets. 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 submitted the accuracy scores to a two-way repeated measures ANOVA with factors number of targets (one vs. T_{same}) and targets to distractors ratio (1:2, 1:3, and 1:5). We did not observe an overall difference between one target (94.5% ± 1.1%) and T_{same} trials (94.2%± 1.2%; $F_{1,14}$ = 0.05, p = .81, $\eta^2_G < 0.001$). However, the manipulation of targets to distractors ratio significantly affected accuracy ($F_{2,28}$ = 4.50, p = .02, η^2_G = 0.042): 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 ($F_{1.37,19.17}$ = 1.33, p =.27, η^2_G = 0.018). 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.

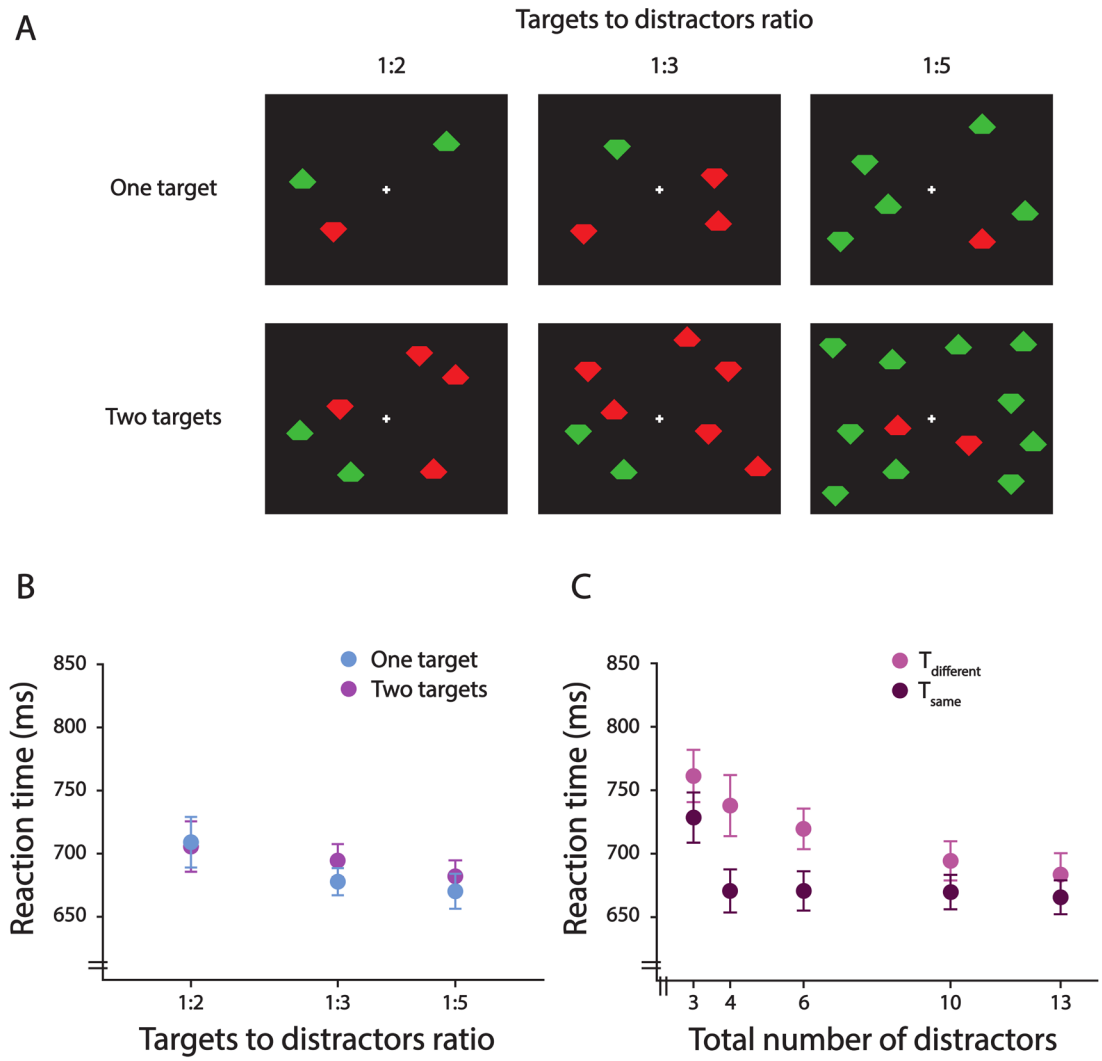

Figure 2. Task and results of Experiment 2. A. Representative displays for equated targets to distractors ratios. Participants reported whether the top or bottom corner was cut-off from one odd-colored target. Either one (top row) or two (bottom row) targets were presented on each trial. On two-target 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 two-target trials.** Reaction time differed depending on whether targets were identical (T_{same}, pink) or opposite ($T_{different}$, dark purple) as well as the number of distractors increased. Error bars represent the between-participants standard error of the mean (s.e.m.).

We next compared reaction times for correct trials with 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). As Figure 2B demonstrates, reaction time decreased as the targets to distractors ratio decreased from 1:2 to 1:5. This result is 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 ($F_{1.21,16.97} = 7.18$, $p = .012$, $\eta^2_G = 0.049$). Posthoc pairwise comparisons with Bonferroni correction showed that reaction time were faster for 1:5 (676ms) condition compared to 1:3 (686ms; $t_{14} = 2.73$, $p = .048$, $d = 0.70$) and 1:2 (707ms; $t_{14} = 3.16$, $p = .021$, $d = 0.81$) conditions. However, we did not observe a significant difference between the one- target (blue markers) and two target conditions (purple markers; $F_{1,14} = 2.53$, $p = .134$, $\eta^2_G = 0.005$) and no interaction with the targets to distractors ratio ($F_{2,28} = 2.08$, $p = .144$, $\eta^2_G = 0.006$). These results suggest that when perceptual grouping was matched between one-target and two-target trials, reaction time was similar. Therefore, to some extent, redundancy cost during discrimination shown in Exp. 1 is determined by the strength of perceptual grouping.

Effect of same or different targets on two-target discrimination

Next, we shifted our focus to the two-target conditions to determine how both targets sharing the same cut-off side and potential response modulates performance as perceptual grouping increases by comparing T_{same} and $T_{different}$ conditions.

We confirmed that participants overall performed the two target conditions well (T_{same}: 93.9% ± 1%). Since the perceptual grouping was always equated between T_{same} and $T_{different}$ trials, we included performance at each total number of distractors used during the two- target conditions (3, 4, 6, 10, or 13 distractors) rather than restricting our analysis to just the subset of conditions used to equate target to distractor ratio with the one-target condition.

A two-way repeated measures ANOVA with factors target shape (T_{same} vs. $T_{different}$) and number of distractors (3, 4, 6, 10, or 13 distractors) was conducted on reaction time. There was a main effect of target shape with reaction time in T_{same} trials (overall mean: 681 ± 15 ms, dark purple markers) being faster than $T_{different}$ trials (721 ± 15 ms, pink markers) across each number of stimuli presented ($F_{1,14} = 65.1$, $p < .001$, $\eta^2_G = 0.086$) (see Fig. 2C). We also confirmed that increasing perceptual grouping facilitated search, as indicated by decreasing reaction times for increasing total number of distractors shown ($F_{4,56} = 17.33$, $p < .001$, $\eta^2_G = 0.118$), which is consistent with prior research (e.g., Duncan & Humphreys, 1989; Bravo & Nakayama, 1992; Song & Nakayama, 2006). There was no significant interaction ($F_{4,56} = 1.96$, $p = .113$, $\eta^2_G = 0.022$). 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, independent of the strength of perceptual grouping.

To summarize, Experiment 2 suggested that unmatched perceptual grouping between one-target and two-target trials in part might have 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).

While the overall redundancy cost due to two targets during discrimination disappeared when perceptual grouping was equated, the difference between T_{same} and $T_{different}$ for the two target condition was still observed even after matching perceptual grouping, hinting at the role of perceptual-response compatibility in this effect. 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 presented. They reasoned this 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 features.

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 following three types of trials: 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.

According to the Theory of Event Coding (TEC), perceptual features and its associated responses get automatically associated and stored in the brain as ‘event files’ (Frings et al., 2020; Hommel et al., 2001; Hommel, 2004, 2005). These stimulus-response associations are assumed to be so strong that mere perception of a particular stimulus automatically activates the associated response codes and vice versa. TEC predicts that performance in both the S_{same} - R_{same}, and $S_{different}$ - R_{same} conditions will be similar as in both of these conditions the same response code gets activated by associated perceptual features. For the $S_{different}$ - $R_{different}$ condition, it predicts that the two targets activate different and competing response codes, which might lead to relatively longer RT compared to the R_{same} 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.

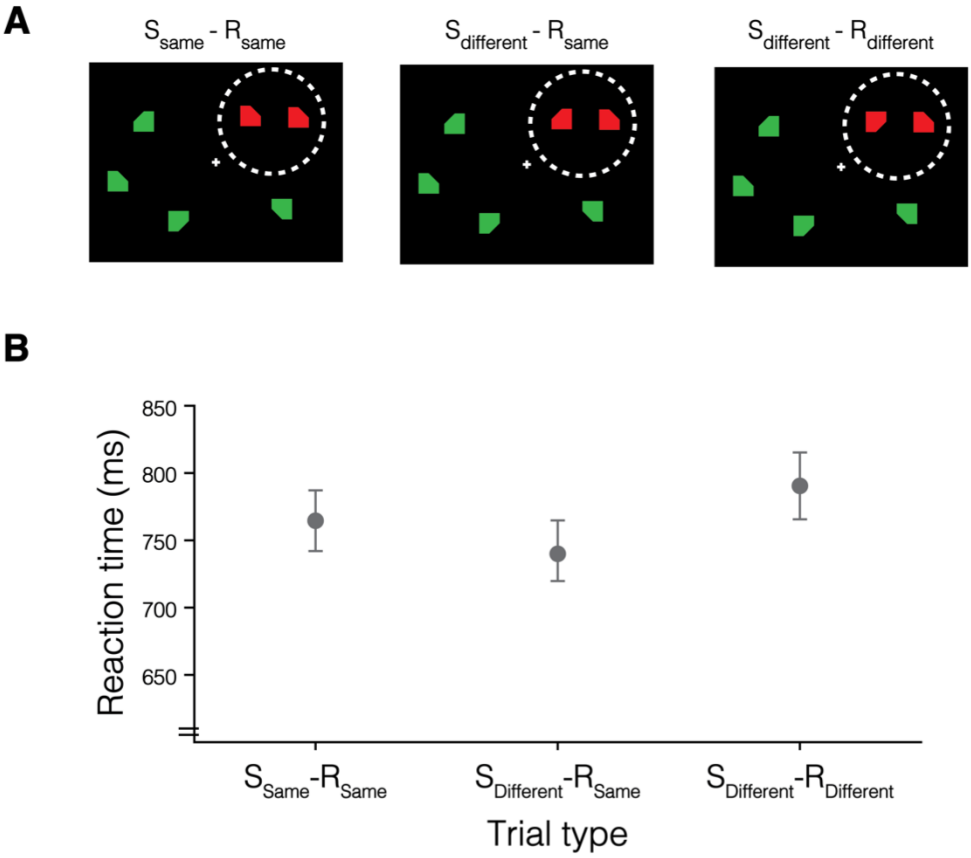

Figure 3. Task and results of Experiment 3. A. Representative displays. Participants reported whether the top or bottom corner was cut-off from one odd-colored target, regardless of whether it was cut-off from the left or right side. Either one or two targets were presented on each trial. On two-target 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 in a one-way repeated measures ANOVA ($F_{2,34} = 9.40$, $p < .001$, $\eta^2_G = 0.118$). Pairwise comparisons revealed percent correct was higher for one-target trials than $S_{different}$ - R_{same} trials ($t_{17} = 4.00$, $p = 0.003$, $d = 0.94$) and S_{same} - R_{same} trials ($t_{17} = 2.85$, $p = 0.03$, $d = 0.671$). However, the difference between S_{same} - R_{same} and $S_{different}$ - R_{same} trials ($t_{17} = 1.83$, $p = .253$, $d = 0.432$) was not significant.

We next examined whether reaction time for correct trials differed between one target and two-target trials. The average reaction time was slower for two target (764ms ±22ms) relative to one target (733ms ±20ms) trials ($t_{17} = 4.81$, $p < 0.001$, $d = 1.13$). 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 whether 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. A one-way repeated measures ANOVA revealed a significant main effect of trial type ($F_{2,34} = 12.36$, $p <.001$, $\eta^2_G = 0.045$). We were interested in comparing the reaction time difference between the $S_{different}$ - R_{same} and the $S_{different}$

- $R_{different}$ conditions, which would tell us about the role of response competition, and between the S_{same} - R_{same} and the $S_{different}$ - R_{same} condition, which would tell us about the role of stimulus competition. In accord with the predictions of a response competition, pairwise comparisons after Bonferroni correction revealed that reaction times were significantly faster for the $S_{different}$ - R_{same} (middle) relative to the $S_{different}$ - $R_{different}$ condition (right; $t_{17} = 6.43$, $p < .001$, $d = 1.52$), with no significant difference between the $S_{different}$ - R_{same} (middle) and S_{same} - R_{same} condition (left; $t_{17} = 2.24$, $p = .115$, $d = 0.53$). Although, the reaction time difference between the S_{same} - R_{same} and the $S_{different}$ - $R_{different}$ conditions ($t_{17} = 2.29$, $p = .104$, $d = 0.54$) did not reach significance it showed the trend in the predicted direction. Overall, these results suggested that responses were faster when both the presented targets were associated with the same response code compared to when both the presented targets were associated with different response.

General Discussion

Previous studies have investigated how redundant targets influence visual search during detection. Here, we extended these investigations to discrimination of a target's features. 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). We hypothesized that a redundant target might influence visual search performance differently depending on whether the task requires detection or discrimination, and whether the information provided by the redundant target is congruent or incongruent.

First, we observed that oddity target detection reaction times were faster when two targets were present compared to one target. This result successfully replicated the redundancy gain found in previous studies (Kummenacher et al., 2001, 2002; Miller, 1982) for two targets in the pop-out search paradigm. In our task, targets were defined by being an oddcolor, and target and distractor colors were 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. This result suggests that redundant targets can incur a redundancy cost for discrimination. In subsequent experiments, we further examined what factors contributed to this redundancy cost. We first 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 partly modulates the

impact of multiple targets. It has been proposed that perceptual grouping efficiency determines pop-out discrimination performance because of the need to allocate focused attention to a target, whereas pop-out detection does not require focused attention (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. Though perceptual grouping appears to partly explain the redundancy cost observed in our pop-out discrimination task, it remains unclear whether perceptual grouping can also explain the redundancy gain in detection. Further experiments are required to confirm the role of perceptual grouping for target detection.

We also demonstrated that performance in pop-out discrimination with two targets was modulated by the competition of potential responses associated with each target, rather than perceptual features. In Experiments 1 and 2 and when comparing the $S_{different}$ - R_{same} and $S_{different}$ - $R_{different}$ conditions in Experiment 3, 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). Those studies and the findings reported here are consistent with a motor coactivation model of redundant target decision making where the activity of processing nodes associated with multiple activated responses are summated (Miller, 1982; Giray and Ulrich, 1993). In such a processing architecture, response conflict could

incur a redundancy cost by either slowing down the rate of evidence accumulation for the eventually executed response or else halting the evidence accumulation process until the conflict has been resolved. Future work should be conducted to differentiate between these possibilities. Regardless of the underlying information processing architecture, our results suggest that response competition may arise during pop-out discrimination when multiple targets differ in their potential responses.

The response competition that we observed is also consistent with the notion of "event files" (Frings et al., 2020; 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.

Our results may also shed light on the mechanisms of attentional selection during visual search. 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, 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. Under this assumption, it is unclear whether both targets would be attended simultaneously (i.e., parallel selection) or each target was serially attended (or some combination of these strategies occurred across trials). While parallel selection has often been assumed in redundant target detection tasks (e.g., Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979; Gratton, et al., 1988; Fournier & Eriksen, 1990), serial selection can in theory also result in response conflict if the response associated with the first target remains activated after attention has been directed to the second target. Moreover, a serial selection account would predict that at least some of the redundancy cost we observe could be driven by an additional time cost associated with re-directing attention from the first to the second target. Future work should be conducted to determine the dynamics of attentional allocation during two target discrimination.

It is also worth noting that in principle, participants did not need to resolve the response conflict in our experiment as any of the associated responses activated by the redundant targets would always be correct. Our result may imply that as soon as two targets are attended, co-activation of opposite responses is automatic and inevitable. Therefore, the observed delay might have arisen due to the process of conflict resolution because participants must select one response only on each trial. One possible future experiment might be able to throw some light on this issue: if participants have the option to press both keys simultaneously whenever both

response codes are activated then there would not be any need to inhibit any particular response, resulting in no redundancy cost if contributed by the inhibitory processes.

To summarize, we believe that a full understanding of redundant target effects in visual search involves consideration of a variety of perceptual and cognitive factors including the level of feature processing required by the task (e.g., mere detection of a target's presence vs. discrimination of a target's shape), attentional selection (of either one or both targets), perceptual grouping processes (Duncan & Humphreys, 1989; Bravo & Nakayama, 1992; Song & Nakayama, 2006; Song et al., 2008) and response conflict (or the absence thereof). Future studies should further investigate the role of each of these factors and develop newer models that can provide a coherent theory to explain both redundancy gain and redundancy cost in a common framework.

Acknowledgements

This project was supported by NSF BCS-1849169 to J.H.S. We thank Drs. Leslie Welch and Elena Festa for their in-depth discussion.

Open Practices Statement

None of the data or materials for the experiment reported here is available online, but the data and materials can be provided upon request. The experiment was not preregistered.

References

Adamo, S. H., Gereke, B. J., Shomstein, S., & Schmidt, J. (2021). From "satisfaction of search" to "subsequent search misses": a review of multiple-target search errors across radiology and cognitive science. *Cognitive Research: Principles and Implications, 6*(1), 1-19. https://doi.org/10.1186/s41235-021-00318-w

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

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. Behavior Research Methods, 37(3), 379–384. doi:10.3758/BF03192707

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

Calder-Travis, J., & Ma, W. J. (2020). Explaining the effects of distractor statistics in visual search. *Journal of vision, 20*(13), 11-11.

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

Corballis, M. C. (2002). Hemispheric interactions in simple reaction time. *Neuropsychologia, 40*(4), 423-434.

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

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods, 39*(2), 175-191.

Flowers, J. H., & Garner, W. R. (1971). The effect of stimulus element redundancy on speed of discrimination as a function of state and process limitation. *Perception & Psychophysics, 9*(2), 158-160.

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

Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., ... & Philipp, A. (2020). Binding and retrieval in action control (BRAC*). Trends in Cognitive Sciences, 24*(5), 375-387.

Garner, W. R., & Flowers, J. H. (1969). The effect of redundant stimulus elements on visual discrimination as a function of element heterogeneity, equal discriminability, and position uncertainty. *Perception & Psychophysics, 6*(4), 216-220.

Giray, M., & Ulrich, R. (1993). Motor coactivation revealed by response force in divided and focused attention. *Journal of Experimental Psychology: Human Perception and Performance, 19*(6), 1278.

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

Grice, G. R., & Canham, L. (1990). Redundancy phenomena are affected by response requirements. *Perception & Psychophysics, 48*(3), 209-213.

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

Grubert, A., Krummenacher, J., & Eimer, M. (2011). Redundancy gains in pop-out visual search are determined by top-down task set: Behavioral and electrophysiological evidence. Journal of Vision, 11(14)(10), 1–10. https://doi.org/10.1167/11.14.10

Hebert, C. R., Li, Z. S., Remington, R. W., & Jiang, Y. V. (2020). Redundancy gain in visual search of simulated X-ray images. *Attention, Perception, & Psychophysics, 82*(4), 1669-1681.

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., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *Behavioral and brain sciences, 24*(5), 849-878.

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

Krummenacher, J., Müller, H. J., Zehetleitner, M., & Geyer, T. (2009). Dimension-and space-based intertrial effects in visual pop-out search: modulation by task demands for focal-attentional processing. *Psychological research, 73*(2), 186-197.

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

Miniussi, C., Girelli, M., & Marzi, C. A. (1998). Neural site of the redundant target effect: Electrophysiological evidence. *Journal of cognitive neuroscience, 10*(2), 216-230.

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., & 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

Olejnik, S., & Algina, J. (2003). Generalized eta and omega squared statistics: Measures of effect size for some common research designs. Psychological Methods, 8(4), 434–447. doi:10.1037/1082-989X.8.4.434

Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus for simple tasks. *Vision research, 34*(13), 1703-1721.

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

Schöpper, L. M., Hilchey, M. D., Lappe, M., & Frings, C. (2019). Detection versus discrimination: The limits of binding accounts in action control. *Attention, Perception, & Psychophysics,* 1-13.

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

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 self terminating 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.

Wolfe, J. M. (2020). Visual search: How do we find what we are looking for?.*Annual Review of Vision Science, 6,* 539-562.

Won, B. Y., & Jiang, Y. V. (2013). Redundancy effects in the processing of emotional faces. *Vision Research, 78*, 6-13.

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