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

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Abstract

To successfully interact 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 *redundancy cost* for discrimination task. 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 redundancy cost compared to perceptual

compatibility. Taken together, our results show how pop-out search involving two targets is

modulated by the level of processing, perceptual grouping, and the 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 multiple 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. 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). Previous studies have sought to understand how redundant target information (number or features) impacts visual search performance (Egeth & Mordkoff, 1991; Estes & Taylor, 1966; Holmgren, et al., 1974; Thornton & Gilden, 2007; Townsend, 1972; Townsend, & Ashby, 1982; van der Heiden, 1975).

Earlier studies investigated the role of redundant target information using either simple detection task or Go/No-go task. When participants are required to simply detect at least one pre-defined target, responses were faster and more accurate when there were two targets compared to

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when there was only one target (e.g., Corballis, 2002; Fischer & Miller, 2008; Giray & Ulrich,

1993; Miller, 1982; Miniussi, Girelli & Marzi, 1998; Mordkoff & Yantis, 1991; Raab,

1962). These findings are in general referred to as *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 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 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 for statistical

facilitation; also see 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 debatable (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 in the

display compared to one target, supporting a motor coactivation hypothesis. Another

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 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 and response features.

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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 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). Redundancy gain

was also reported in 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. Each of these studies consistently demonstrating redundancy

gain primarily required target detection such that all targets yield the same target-present or-

absent responses.

Much less is known about how redundant targets interact with visual search when fine-

detail target feature discrimination is required and the responses could conflict among the two

targets. We aimed to examine whether the redundancy gain as seen for detection tasks also

occurs in discrimination tasks. 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, visual search performance differs as a function of distractor numbers in the

context of pop-out search for detection compared to discrimination task (Bravo & Nakayama,

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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 (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. 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). 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 in a target detection task because more targets in the search display leads

to faster detection (Krummenacher, et al., 2001; Miller, 1982). However, we expect that target

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discrimination task performance may differ based on the perceptual and attentional requirements

of fine discrimination (Bravo & Nakayama, 1992; Flowers & Garner, 1971; Garner &

Flowers, 1969; Schopper et al., 2019) (Exp. 1), the strength of perceptual grouping imposed by

the ratio of target and homogeneous target/distractor ratio (Exp. 2) and the contribution of

differential perceptual or response activation associated with different targets (Exp. 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 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

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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 ($T_{different}$).

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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 $1.7\% \pm 0.1\%$ (standard error of the mean, s.e.m.) of detection trials and $1.4\% \pm 0.1\%$ 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 ($96.5\% \pm 0.6\%$ s.e.m.), one-target ($98.7\% \pm 0.3\%$), and two-target ($99.4\% \pm 0.2\%$). 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

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($F_{2,14} = 45.24$, $p < 0.001$, $\eta^2 = 0.17$). 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) facilitates or deteriorates visual

search. We observed faster reaction time in the two-target trials compared to one-target trials

(blue; $t_{14} = 4.65$, $p < 0.001$, $d = 1.70$). 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

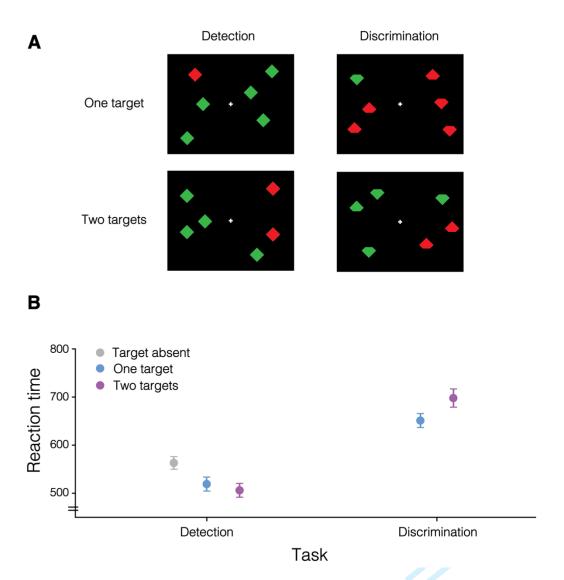trials (gray; $t_{14} = 8.46$, $p < 0.001$, $d = 2.18$).

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.).

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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}). 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 < 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} in which both oddity targets share the same cut-off side (676 ± 15 ms; $t_{14} = 3.26$, $p < 0.01$, $d = 0.84$) and $T_{different}$ in each oddity target had a different cut-off side (721 ± 24 ms; $t_{14} = 4.91$, $p < 0.005$, $d = 1.27$) were significantly slower than the one-target condition. 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 ($t_{14} = 3.17$, $p < 0.05$, $d = 0.82$). We conjecture that this discrepancy between the T_{same} and $T_{different}$ conditions occurred because of different target shapes, associated responses, or both, which we addressed further in Exp. 3.

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

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(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,

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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) 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.

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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.
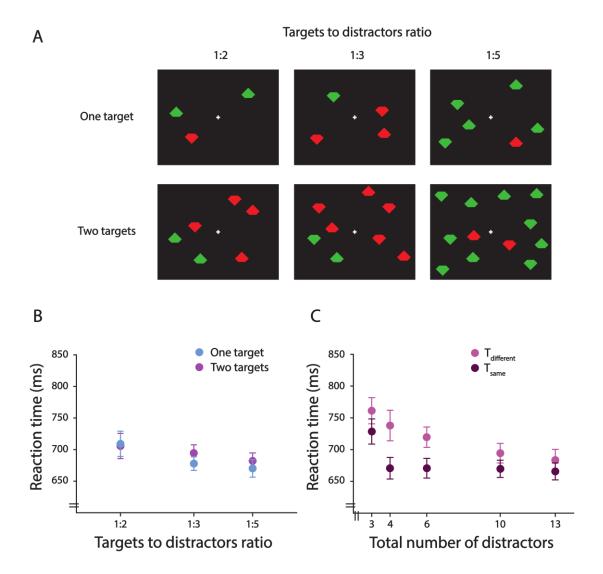
Figure 2. Task and results of Experiment 2. A. Representative displays for equated targets to distractors ratios. Participants reported whether the top or bottom corner was cut-off from one odd-colored target. Either one (top row) or two (bottom row) targets were presented on each trial. On two-target 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.).

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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 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 ($F_{2,14} = 7.18$, $p < 0.005$, $\eta^2 = 0.05$) 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. 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 stimuli 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.

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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 ($F_{1,14} = 65.1, p < 0.001, \eta^2 = 0.09$). We also confirmed that increasing perceptual

grouping facilitated search, as indicated by decreasing reaction times for increasing total number

of distractors shown ($F_{4,14} = 17.33, p < 0.01, \eta^2 = 0.15$), 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, 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

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simultaneously 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 aspects.

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

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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 a 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

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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

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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 $1.1\% \pm 0.2\%$ of one-target trials, and $1.1\% \pm 0.4\%$,

$0.8\% \pm 0.3\%$, and $0.6\% \pm 0.3\%$ of S_{same} - R_{same}, $S_{different}$ - R_{same}, and $S_{different}$ - $R_{different}$ trials

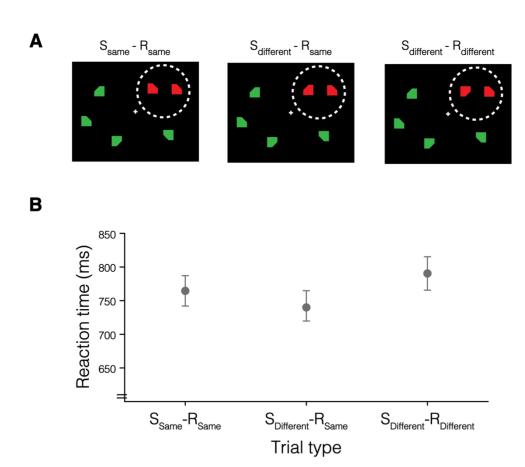excluded from analysis. During analysis, subsequent pairwise comparisons were Bonferroni

corrected.

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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.).

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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 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. 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

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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 how redundant targets influence visual search during detection. Here, we extended these investigations to discrimination. As 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 odd-color, 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

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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 might lead to a redundancy cost for discrimination. In subsequent

experiments, we further examined what factors contributed to this redundancy cost. 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 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 could partly explain the

redundancy cost observed in our pop-out discrimination task, it is still 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 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.

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.

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 by the task demands.

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 perceived, 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. For instance, if participants have the option to press both the keys simultaneously

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whenever both the 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 redundancy gain (as seen in detection task), and redundancy cost (as seen in discrimination task) can be better explained by considering an attentional explanation involving perceptual grouping (Duncan & Humphreys, 1989; Bravo & Nakayama, 1992; Song & Nakayama, 2006; Song et al., 2008) and event coding involving stimulus-response coactivation (Frings et al., 2020; Hommel et al., 2001; Hommel, 2004, 2005). Future studies should investigate the role of perceptual grouping and stimulus-response consistency and propose newer models that can provide a coherent model that explains both redundancy gain and redundancy cost in a common framework.

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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.

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