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Inhibition in large set sizes depends on search mode, not salience

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Abstract

Attention can be attracted to salient items in a visual scene. Recent studies have shown that when the feature of an irrelevant salient item is known, it can be suppressed below baseline leading to facilitated search. Wang and Theeuwes (*Experimental Psychology: Human Perception and Performance*, *46*(10), 1051–1057, 2020) criticised previous inhibition studies by claiming that the sparse displays attenuated the salience of the distractors. In their study they increased the number of display items (i.e., set size), and found that an irrelevant salient distractor captured attention. The current paper argues that the displays used by Wang and Theeuwes encouraged participants to use a singleton search mode, in which participants actively look for salient regions to find the target and consequently do not inhibit salient items. Specifically, their displays included multiple repeated non-target shapes, so that the target became a singleton. We used two search displays with ten items, one with repeated non-targets (R-NT displays), allowing a singleton search mode, and one with heterogeneous non-targets, encouraging a feature search mode. In Experiment 1 the singleton distractor was inhibited in the heterogeneous condition, but not in the R-NT condition. Experiment 2 intermixed the two display types in unbalanced blocks. When the majority of trials had heterogeneous non-targets, inhibition was observed for both the heterogeneous displays and the R-NT displays. Conversely, when R-NT displays were the majority, inhibition was attenuated for both display types. These results show that distractor features can be suppressed at large set sizes dependant on the search strategy promoted by the displays.

Keywords Visual search · Attention · Inhibition

Introduction

When navigating a visual environment, different mechanisms can compete for control of an observer's attention. One competition is whether attention is initially directed to items that match the 'top-down' goals of the participant, or whether attention is captured, 'bottom-up', by items that saliently differ from their surroundings (Wolfe, 2021). A top-down goal can be initiated when the searcher knows the specific feature of the sought-after item. This results in an increased sensitivity for items with matching features, guiding attention to target-similar items (Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Wolfe, 2021). For example, searching for a blue circle would lead to an attentional bias for blue and curved items (e.g., Duncan & Humphreys, 1989; Folk et al., 1992).

Attention can also be guided or 'captured' reflexively to visually salient regions in a bottom-up manner, regardless of top-down goals or task demands. Visually salient items are items that significantly differ from their surroundings (Theeuwes, 1992); for example, a single red item among several green items. Salient items have been argued to intrinsically send an 'attend-to-me' signal to the visual system (Sawaki & Luck, 2010). Experimentally, attentional capture by salient items is often examined with the *additional singleton paradigm* where participants search for a target (e.g., a shape) while ignoring an irrelevant salient distractor (e.g., a colour). Variations in response times (RTs) and the location of the first eye-movement reveal if the distractor captured attention (Gaspelin et al., 2017; Geng & DiQuattro, 2010).

While it has been argued that any salient item should capture attention (Theeuwes, 2004), there are instances where seemingly salient items do not capture attention but instead facilitate search for the target (Gaspelin et al., 2015). These shorter RTs on distractor-present trials

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(compared to distractor-absent trials) suggest that sensitivity for the singleton was in fact lower than the average non-target item. Seemingly, there is an attentional avoidance of this salient distractor, more so than the other non-salient non-targets. Originally, Gaseplin and colleagues (2015) claimed that this supported the signal-suppression hypothesis (Sawaki & Luck, 2010), proposing that the attend-to-me signal emitted by salient distractors could be suppressed via top-down goals. Subsequent research quickly revealed that an irrelevant salient distractor can only be actively suppressed when its features remain constant over a series of trials (e.g., Becker, 2007; Gaspelin et al., 2019). Furthermore, when distractor colours are compared against equally salient neutral values in masked probe trials suppression is still observed (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022). Thus, a feature-suppression mechanism appears much more plausible for the source of the inhibition effect (e.g., Treisman & Sato, 1990); a salient item can be suppressed via its feature value. However, a recent study has challenged this assertion by claiming that the distractors used in these inhibition studies were not in fact salient (Wang & Theeuwes, 2020).

In the aforementioned inhibition studies, visual search arrays consisted of only four heterogeneous shapes (e.g., Gaspelin et al., 2015; Hamblin-Frohman & Becker, 2022). Wang and Theeuwes (2020) argued that this rendered the singleton distractor non-salient (as well as the target non-salient; see also Theeuwes, 2004) because the distractor did not stand out ('pop out') from the heterogeneous non-target shapes. They claimed that the sparse displays did not generate enough feature contrast to render any item salient. In their inhibition study, they varied the set size (number of non-target items) while participants searched for a specified shape target and tried to ignore a singleton distractor (differing in colour) that was present on 50% of the trials. Critically, the sparse displays used in previous experiments (set size of four) were compared against more dense set sizes (six and ten). Like Gaspelin and colleagues (2015), they also included probe trials, in which four differently coloured characters were presented briefly, one of which always had the target colour or distractor colour (50%) and participants had to report all characters. In set size four, they did not observe any inhibition in the visual search RTs, but did find lower probe recall for characters within the distractor colour than the target/non-target colours (i.e., inhibition). In the set size ten, and to a lesser extent set size six, they observed distractor capture effects; longer RTs on distractor-present trials compared to absent trials, and higher probe recall for the distractor colour. Wang and Theeuwes (2020) concluded that truly salient items cannot be inhibited as the only difference between the set size four and ten conditions were the relative saliency of the distractors.

There are, however, some potential issues with the set size manipulation of Wang and Theeuwes (2020). In their set size four condition, the search array shapes included a circle, diamond, hexagon and square. In their set size ten condition, no new shapes were added, so that the array now comprised four hexagons, four squares, one circle, and one diamond. Thus, the target was a deviant in these displays and could now conceivably be considered a singleton. Bacon and Egeth (1994) noted that search could follow two different strategies depending on the composition of the non-target elements. When non-targets were homogenous in shape, rendering the target unique in form, participants adopted a singleton search mode where attention is biased to all items that are unique or salient. Consequently, singleton distractors usually capture attention in singleton search mode. When non-targets were heterogeneous in shape and the target was not unique, participants adopted a feature search mode, in which attention is biased to the exact defining feature value of the target. In feature search mode conditions, Bacon and Egeth (1994) did not observe capture from singleton distractors.

With respect to Wang and Theeuwes' design, their larger set sizes used only two singleton shapes (not including the salient distractor) and several repeated non-target shapes. Thus, it is plausible that searchers could have adopted a singleton-detection mode to search for the target. As seen in previous research, singleton search strategies lead to singleton distractor capture and prevent inhibition (Bacon & Egeth, 1994; Gaspelin et al., 2015). In the small set size (four) condition, the non-target shapes were all heterogeneous, making it plausible that participants adopted a feature search mode, which rendered them immune to salient distractors. Thus, a difference in search strategy between the large and small search set sizes used may explain the lack of inhibition observed at large set sizes.

Experiment 1

Experiment 1 examined inhibition in a large set size by comparing a fully heterogeneous search array (i.e., all different shapes) against a search array with repeated non-target (R-NT) items (as in Wang & Theeuwes, 2020). In the heterogeneous search array, participants should adopt feature search mode, which should lead to inhibition of the singleton distractor. Conversely, in the R-NT search block participants may adopt a singleton search mode, which should lead to capture by the salient distractor. If Wang and Theeuwes (2020) are correct that salient items cannot be suppressed at large set sizes, then distractor capture (or at least an absence of inhibition) should be observed for both search arrays. Conversely, if inhibition is solely due to search strategy, then inhibition should be observed in the heterogeneous search array (requiring feature search) but not in the R-NT displays (potentially encouraging singleton search). Masked probe trials were used to assess the attentional biases both towards the target colour and away from the distractor colour (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022; see also Kerzel & Renaud, 2023). Importantly, the probe trials test the attentional biases towards target and distractor colours against neutral colour values (not encountered in the search trials), removing the influence of salience from probe performance and distinguishing between target-feature activation and distractor-feature suppression.

Methods

Participants

To assess the required sample size for the study, we used the distractor capture effect observed in Wang and Theeuwes' (2020) set size ten condition ($t(23) = 5.07$). To achieve a power of 95% (with 90% assurance) the BUCSS tool suggested a planned sample size of 30 participants (Anderson et al., 2017). Thirty-five paid participants from the University of Queensland participated; three were excluded for having low search accuracy (< 80%), leaving 32 in the final analysis (M age = 22.9 years ($SD = 1.7$); 21 female). The study was approved by the University of Queensland ethics board.

Apparatus

Stimuli were presented on a 21-in. CRT monitor with a refresh rate of 85 Hz. A chin and headrest were used to hold the participant's heads 600 mm from the screen. The experiment was controlled by Python's PsychoPy (Peirce, 2007).

Stimuli

All stimuli were presented against a white background. For the search displays, ten stimuli were presented equidistantly around fixation (radius: 7.32°). The target stimulus was always a diamond (height: 2.02°). In the heterogeneous non-target search condition, the other nine shapes were all different: a square (height: 1.43°), circle (radius: 0.88°), hexagon (height: 2.05°, width: 1.03°), pentagon (1.73° × 1.61°), cross (1.93° × 1.93°), star (radius: 1.11°), trapezoid (height: 1.29°, mean width: 1.76°), triangle (height 1.61°), and octagon (radius: 0.82°). In the R-NT condition, the non-targets consisted of three squares, circles and hexagons, so that the target was the only unique shape in the search display. On distractor-absent trials all items had the same colour (referred to as the target colour), on the distractor-present trials a single non-target was changed to a different colour (referred to as the distractor colour). There were two target/distractor colour pairs used for the search trials that were maximally different: gold (RGB: [193,145,38]) and blue (RGB: [25,164,199]), and red (RGB: [255,92,104]) and green (RGB: [133,164,74]). These colours were randomly assigned to search conditions as wells as to the roles of target and distractor values. This ensured that participants started each search block with a new colour pairing. Within each of the search stimuli were response-defining characters '<' or '>' (height: 0.46°). See Fig. 1 for examples of the search displays.

In the probe trials, four circles (radius: 1.03°) appeared in cardinal directions around fixation (5.86° from centre). The critical probe contained a numeral (1–9), while the other three probes contained random capital characters (selected from the following set: E, G, Y, K, C, M, W, A, V, F, R). All probes had a height of 0.46°, and each probe contained a unique colour. One of the colours was either the target or distractor colour from the search trials. The other three colours were randomly selected from the set of purple on each trial (RGB: [184,123,210]), orange (RGB: [229,122,54]), pink (RGB: [228,101,180]) and teal (RGB: [86,170,120]). Probes were backward masked with coloured checkerboard masks of the same size. See Fig. 2 for examples of the probe displays.

Design and procedure

The experiment was divided into two counterbalanced blocks: a heterogeneous search and a R-NT search. Each block had 240 search trials and 120 probe trials. On 50% of search trials (120 trials per block) the distractor was present.

Each trial began with a 1,000-ms fixation cross. For the search trials, the search stimuli were displayed until a response was recorded. Participants were instructed to locate the diamond shape and to quickly and accurately respond to the character contained within, using the left or right arrow keys (left for '<', right for '>'). Participants were informed about the irrelevant colour singleton distractor and instructed to ignore it. If a response was recorded after 2,750 ms or was incorrect, error feedback was delivered.

For the probe trials the four colours were presented without response characters for 400 ms. Subsequently the response characters were presented on top of the probe stimuli for an additional 100 ms before being masked with a checkerboard pattern. Participants were instructed to report the identity of the single number that appeared among the different characters. On 50% of probe trials, one of the probes had the colour of the target (and non-targets) from the search trials, whereas on the other 50% the probe display contained the distractor colour. These search-related colours were not predictive of the numeral's location. That is, on 25% of trials the critical probe numeral was on one of the search-related colours (30 trials). On the other 75% of trials the numeral was on a neutral colour-value, which had

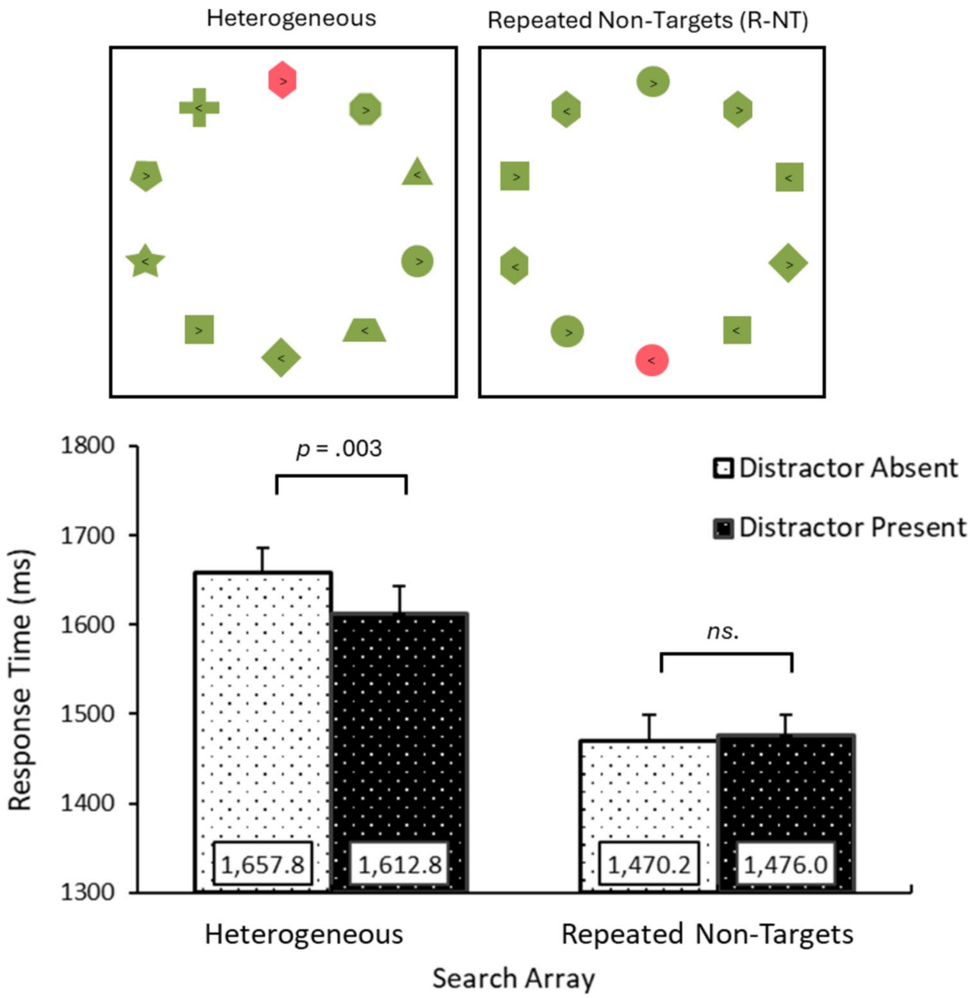

Fig. 1 **Top:** The visual search displays used. In both conditions, participants searched for the diamond target and responded to direction of the arrow inside the target. On 50% of trials one of the items had a different colour (distractor). In the heterogeneous non-target condition a feature-search mode was promoted. In the R-NT condition each non-target shape was repeated twice. **Bottom:** Response time (RT) data. Results revealed that an inhibitory effect in the heterogeneous search condition. RTs were faster on distractor-present trials compared to distractor-absent trials. Neither distraction nor inhibition was observed in the R-NT block. Error bars represent within-subject 95% confidence intervals (Loftus & Masson, 1994)

not been used in search. Participants completed ten practice search trials before each block commenced.

Results

Search response times

In visual search, 8.1% of trials were excluded for responses slower than 2,750 ms, and 6.1% of trials were excluded for incorrect responses. To test whether distractor presence facilitated or hindered search, a 2 (Search Set: Heterogeneous, R-NT) × 2 (Distractor: Present, Absent) repeated-measures analysis of variance (ANOVA) was conducted on visual search RTs. A main effect of distractor presence emerged, $F(1,31) = 4.69$, $p = 0.038$, $\eta^2_p = 0.13$, reflecting faster RTs in distractor-present trials (for means see Fig. 1). RTs were longer in the heterogeneous search condition than the R-NT search, $F(1,31) = 83.23$, $p < 0.001$, $\eta^2_p = 0.73$. Crucially, these effects were qualified by a significant interaction, $F(1,31) = 7.81$, $p = 0.009$, $\eta^2_p = 0.20$. Paired two-tailed t-tests revealed that the inhibition effect (faster RTs on distractor-present trials) was observed in the feature search condition $t(31) = 3.24$, $p = .003$, $BF_{10} = 12.85$. In the singleton search condition, no RT differences were observed between distractor-absent and -present trials, $t(31) = 0.50$, $p = 0.624$, $BF_{10} = 0.21$, reflecting a failure to observe suppression *or* capture.

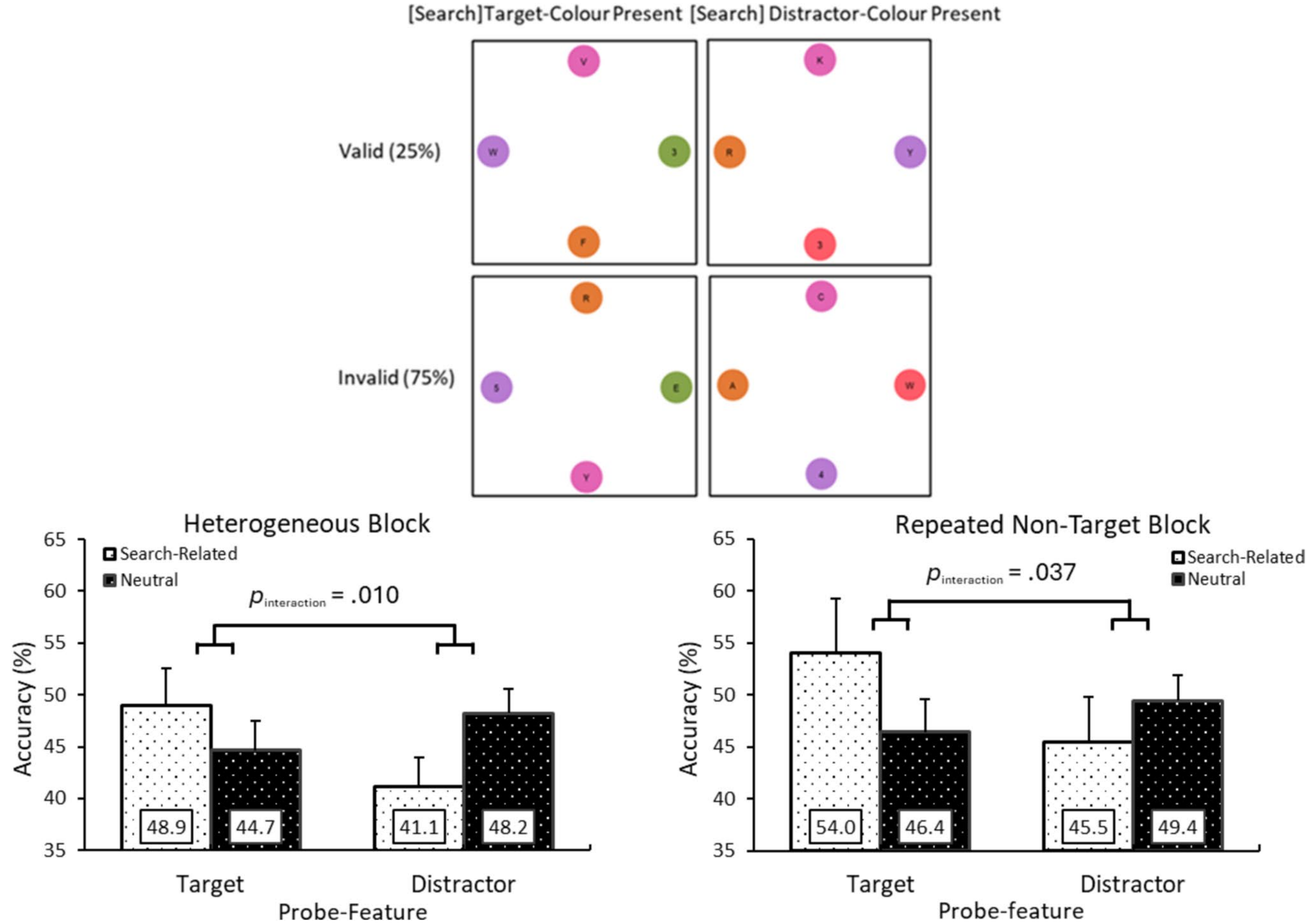

Fig. 2 **Top:** Example of the probe displays. The coloured circles preceded the characters by 400 ms. Then both were displayed for 100 ms. Participants were required to report the identity of the numeral that appeared (1–9). Each probe trial contained either the colour associated with the target in visual search (here: green) or the colour associated with the distractor (here: red). The critical numeral could appear either on the search related colour or on one of the neutral colours. **Bottom:** Response accuracy data. In both heterogeneous and R-NT conditions an interaction was observed. Overall, there was an inverse congruency effect for distractor-colour probes. Probe accuracy was lower when the critical numeral was on the distractor colour compared to a neutral colour, suggesting a suppressive bias away from the distractor colour. For target-colour probes the opposite was true, accuracy was higher when the numeral was on the target colour, indicating a target-feature enhancement effect. Importantly these effects did not vary between search blocks. Error bars represent within-subject 95% confidence intervals (Loftus & Masson, 1994)

Probes

Probe accuracy was initially analysed in a 2 (Search Set: Heterogeneous, R-NT) × 2 (Probe Item: Target, Distractor) × 2 (Item Type: Search-Related, Neutral) repeated-measures ANOVA. Critically, the probe item x item type interaction was significant, $F(1,31) = 9.75$, $p = 0.004$, $\eta^2_p = 0.24$. When collapsing over search set, pairwise comparisons revealed the predicted congruence effects. For target-colour present probes, accuracy was higher when the response numeral was on the target colour compared to when it was on a neutral colour, $t(31) = 2.21$ $p = 0.035$, $BF_{10} = 1.60$, indicating anecdotal evidence for a bias towards the target-related colour. The inverse was true for distractor-colour present probes. Accuracy was higher when the response numeral was on a neutral colour than when it was on the distractor-colour, $t(31) = 3.18$ $p = 0.003$, $BF_{10} = 11.36$, indicating strong evidence for a bias away from the distractor colour.

These results replicated the previous findings of masked probe trials revealing both a target-feature enhancement and a distractor-feature suppression effect (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022). Of interest for the current study was whether these results differed across search conditions. The three-way interaction returned as non-significant, $F(1,31) < 0.01$, $p = 0.970$, $\eta^2_p < 0.01$, showing that congruence effects for the targets and distractor probe trials did not differ across search blocks.

Analysing the congruency effects for target and distractor-coloured probes separately for the heterogenous block, $F(1,31) = 7.64$, $p = 0.010$, $\eta^2_p = 0.20$ and the R-NT block,

$F(1,31) = 4.77$, $p = 0.037$, $\eta^2_p = 0.13$, there was a significant interaction between probe item and item type. T-tests revealed that in the heterogeneous block a significant distractor-feature suppression effect was observed, $t(31) = 3.20$, $p = 0.003$, $BF_{10} = 11.94$, but no difference was observed for target-feature enhancement, $t(31) = 1.48$, $p = 0.149$, $BF_{10} = 0.51$. In the R-NT block there was trend towards target-enhancement, $t(31) = 1.99$, $p = 0.055$, $BF_{10} = 1.08$ and no evidence for distractor-suppression $t(31) = 1.57$ $p = 0.127$, $BF_{10} = 0.58$.

Discussion

Experiment 1 revealed behavioural differences between two types of search arrays. When non-target elements were heterogeneous, RTs were faster when the distractor was present compared to absent, indicating that the distractor feature was inhibited. This shows a clear inhibition effect for the repeated-distractor in the search array that promoted a feature-detection mode. Conversely, in the R-NT block where a singleton-detection mode was plausible, there was no evidence for inhibition in the search trials. Surprisingly, capture was not observed in this condition (contrary to predictions) and failed to replicate the results of Wang and Theeuwes (2020). Bottom-up capture can be difficult to observe and may be dependent on particulars of the stimulus or apparatus set up (e.g., Becker, 2007, 2010; Breker et al., 2017; Wienrich & Janczyk, 2011). For example, Stilwell and Gaspelin (2021) failed to observe distractor capture in large set size search displays in multiple experiments, and only replicated the distractor capture effect when the exact stimuli from Wang and Theeuwes (2020) were used (see also Stilwell et al., 2022). A recent study by Stilwell and colleagues (in press) also failed to note either inhibition or distractor capture using the displays of Wang and Theeuwes (2020). A plausible explanation is that some element in the displays of Wang and Theeuwes (2020) maximised the probability of participants adopting a singleton search mode, whereas in other variations of this display, the chance of a feature search mode being used was higher.

While the search data revealed clear differences between the heterogeneous and the R-NT search displays, the probe trials no such dissociation. In both blocks, the key interaction between probe position and probe-feature identity was present replicating previous studies using similar probe designs (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022). A congruency effect was present for target-related colours and the inverse for the distractor-related colours, implying that both target-feature enhancement and distractor feature suppression were influencing the allocation of attention in the search displays.

If this is the case, that there were equivalent biases towards the target colour and away from the distractor colour in both search blocks, then it is unclear why inhibition was not observed in the R-NT condition. There are two possibilities for why this is the occurred. Theeuwes (2004) argued that adding heterogeneous elements to a display could render the target and distractor less salient, thus it could be argued that the singleton distractor in the R-NT display was less salient that the same distractor in the heterogeneous display. Even though the distractor colour was suppressed (as shown from the probe trials) the bias could not overcome salience of the distractor in the search trials, leading to a lack of inhibition. Conversely, the difference in inhibition effect may in fact be due to our original search-mode hypothesis. In the heterogenous block a feature-search mode was encouraged allowing inhibition to operate on the display. In the R-NT block it was plausible to search with a singleton-detection mode. Even though the colour-feature of the distractor was suppressed, top-down attention would still be attracted towards the colour-singleton. These competing drives may account for the lack of both inhibition and capture observed in the R-NT search trials.

Experiment 2

Experiment 2 tested whether the lack of inhibition observed in the R-NT displays was due to an increased distractor salience (as compared to the heterogeneous displays) or due to the enablement of a singleton-search mode. To that end, Experiment 2 intermixed the two search displays in unbalanced blocks. This was done to encourage a consistent search mode that persisted across the whole block (e.g., Leber & Egeth, 2006a, 2006b). In the 'feature search' block the majority of trials had heterogeneous non-targets and infrequent R-NT search trials and in the 'singleton search block', this mapping was reversed.

If inhibition effects are due to distractor saliency differences from the search displays, then inhibitory effects for the heterogeneous non-target displays and a lack of inhibition for the repeated non-targets should be observed independent of block type. Conversely, if search strategy determines inhibition, then inhibition should be observed for both search-display types when the majority of trials have heterogeneous non-targets (feature-search block), and no inhibition should be observed in any of the displays in the majority R-NT search block ('singleton-search block').

We could not include any probe trials in Experiment 2 due to time constraints on testing. Rather, inhibition can be inferred from the search times in visual search. Inhibition of the distractor should result in shorter RTs when the distractor is present than when it is absent (and cannot be clearly distinguished from target activation effects in visual search; see above).

Methods

Participants

Thirty-two participants from the University of Toronto participated for course credit; two were excluded for having low search accuracy (< 80%), leaving 30 participants in the final analysis (*M* age = 19.2 years (*SD* = 1.9); 24 female). The study was approved by the University of Toronto ethics board.

Apparatus and stimuli

Stimuli were presented on a 24-in. Dell S2417DG monitor with a refresh rate of 144 Hz**.** Stimuli sizes and positions were adjusted to match those of Experiment 1.

Design and procedure

Participants completed two counter-balanced blocks of trials. To encourage different search strategies the proportions of trial types varied in each block. In the feature search block, 75% of trials showed the heterogeneous non-target displays and 25% showed the repeated non-target displays. In the singleton search block 75% were R-NT trials and 25% were heterogeneous. Target and distractor colours were the same within a block, for example, both heterogeneous and R-NT displays had the same colour values within the feature-search block, while a new set of colours was used in the singleton-search block. The colours used were the same as in Experiment 1.

The procedure was identical to that of Experiment 1, except for the exclusion of the probe trials. Participants completed 360 search trials in each block (270 for the majority display, 90 for the minority). On 50% of trials the distractor was present. Participants completed 30 practice trials before each block, which were not analysed.

Results

Trials were excluded for slow responses (> 2,750 ms: 6.7% of trials) and for incorrect search responses (5.4% of trials). To evaluate the opposing prediction, the effects were analysed within each search block. For the Feature-search block, a 2 (Search Display: Heterogeneous, R-NT) × 2 (Distractor: Absent, Present) repeated-measures ANOVA on search RTs, revealed a main effect of Distractor, $F(1, 29) = 14.98$, $p < 0.001$, $\eta^2_p = 0.31$; reflecting shorter RTs for distractor present trials (see Fig. 3). There was no effect of display type, $F(1, 29) = 2.33$, $p = 0.138$. Importantly there was no interaction between display and distractor presence, $F(1, 29) = 0.60$, $p = 0.445$, reflecting that inhibition occurred for both display types. Two-tailed follow-up t-tests supported this, showing significantly shorter RT for distractor present than absent trials for the Heterogeneous search displays, $t(29) = 4.07$, $p < 0.001$, $BF_{10} = 89.35$, as well as for the R-NT displays, $t(29) = 2.57$, $p = 0.015$, $BF_{10} = 3.13$.

For the Singleton-search block the same 2 × 2 repeated-measures ANOVA revealed a significant effect for Display type, $F(1, 29) = 14.62$, $p < 0.001$, $\eta^2_p = 0.34$, reflecting longer RTs for the heterogeneous search displays than the R-NT displays. There was no effect of Distractor, $F(1, 29) = 0.65$, $p = 0.426$, and no interaction, $F(1, 29) = 0.02$, $p = 0.897$. Follow-up comparisons revealed no differences between distractor-absent and present trials for the Heterogeneous

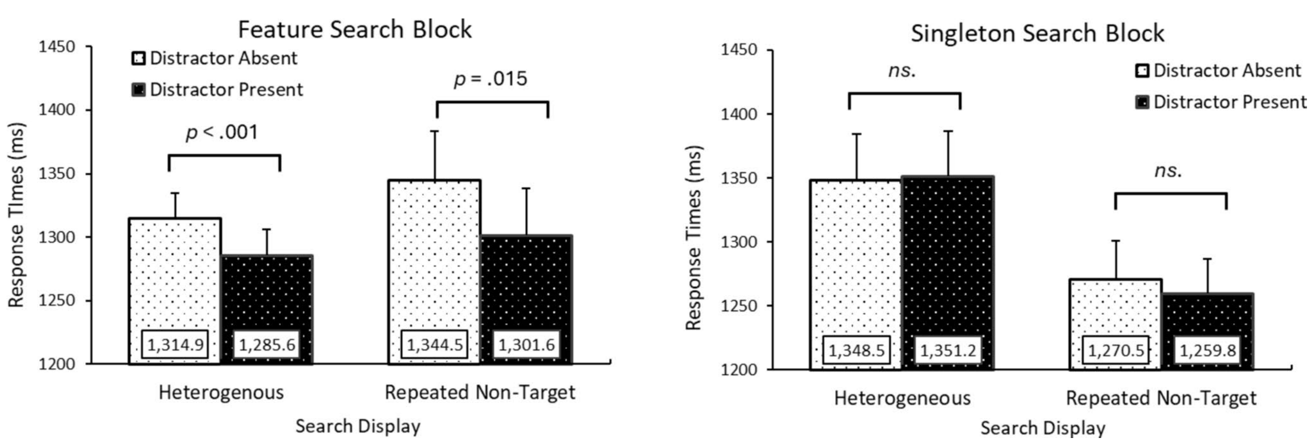

Fig. 3 Response time (RT) results from Experiment 2. **Left:** In the Feature search block, 75% of trials had heterogeneous non-targets, encouraging a feature search mode. Inhibition was observed for both displays, i.e., RTs were shorter when the distractor was present compared to absent. **Right:** In the Singleton search block 75% of the trials were repeated non-target displays, allowing participants to adopt a singleton search strategy. No inhibition was observed for either display type. Error bars represent within-subject 95% confidence intervals (Loftus & Masson, 1994)

displays, $t(29) = 0.46$, $p = 0.650$, $BF_{10} = 0.21$, or for the R-NT displays, $t(29) = 0.90$, $p = 0.374$, $BF_{10} = 0.28$.

Discussion

The results of Experiment 2 confirmed that the presence or absence of inhibition critically depends on the search strategy, not on the composition of the display or the saliency of the distractor: In the feature-search block, inhibition was observed for both display types, regardless of whether they contained all heterogeneous non-targets or repeated non-targets. By contrast, when the majority of trials were R-NT displays, no inhibition was observed. Importantly, display type within each block had no influence on whether or not inhibition occurred. This suggests that stimulus factors, specifically the relative saliency of the singleton-distractor, did not have any influence on inhibitory biases. The deciding factor was which display type formed the majority within each block, which in turn shaped the search strategy. Inhibition occurred when a feature search strategy was promoted and was attenuated when a singleton-detection mode was possible, in line with our original contention.

General discussion

The current experiments compared inhibitory effects in large (ten-item) set sizes in two different search contexts: when the non-target shapes were heterogeneous vs. when they were repeated in the search displays. In Experiment 1, the two displays were presented in separate blocks, whereas in Experiment 2 the displays were intermixed but biased towards one display type in each block. When the majority (or all) of the trials had completely heterogeneous non-target items a feature search strategy was encouraged (Bacon & Egeth, 1994). In these conditions we observed inhibition of the distractor. Importantly, the distractor was also inhibited in the repeated non-target displays in the intermixed condition that featured a majority of heterogeneous displays in Experiment 2. Conversely, when the majority (or all) of trials were R-NT displays no inhibition was observed and critically this also occurred for the intermixed heterogeneous trials in the intermixed condition of Experiment 2 that contained mostly R-NT trials. These results reveal that inhibition was dependent on the search strategy encouraged by the majority of displays, and was not due to salience differences between the two display types. Furthermore, it shows that inhibition can operate in large set size displays when singleton distractors are salient.

The salience of targets and distractors can be reduced via increasing the sparsity of displays (Theeuwes, 2004) or increasing non-target heterogeneity (Duncan & Humphreys, 1989). Previous inhibition studies have shown distractor inhibition in displays that were both sparse and heterogeneous (e.g., Gaspelin et al., 2015; Hamblin-Frohman & Becker, 2022). This has led others to suggest that distractor features are only able to be suppressed when they are non-salient (e.g., Wang & Theeuwes, 2020). In the current experiment, we show that inhibition can occur under circumstances where distractors and targets are salient. Specifically, the R-NT condition fulfilled the requirements of salience-driven capture as described by Wang and Theeuwes (2020). Our displays were not sparse, the target was a singleton, and the distractor was unique in colour. A recent study by Stilwell and colleagues (in press) examined how salient target and distractors were in small and large set size search displays. They revealed that the singleton distractor was more salient when the shapes were filled with colour (as in the current design) compared to the unfilled coloured outlines used in Wang and Theeuwes (2020), and more salient in larger than smaller set sizes. These results confirm that the singleton distractor was of adequate salience in the R-NT displays and that the inhibition observed in the R-NT search trials cannot be attributed to a lack of salience. Moreover, some results by Stilwell and colleagues (2023) suggest that the relationship between salience and suppression may have been too simplistic. The authors compared high and low salience distractors and found that high salience distractors led to larger oculomotor suppression effects. This reflects that altering the salience of the singleton distractor may result in varying degrees of inhibitory effects. The current results corroborate this claim, by showing that highly salient distractors can be effectively suppressed in feature search mode.

A singleton-search mode can be used when a search target item can be defined by its uniqueness, whereas a feature-search mode is enforced when the only way of locating the target is by tuning to its specific feature values (Bacon & Egeth, 1994). The heterogeneous displays used in the current experiment seem to fulfill that condition, as the target could only be found by its specific form and the only singleton was the distractor colour. The R-NT displays, however, do not fully map onto a singleton-detection mode. The strongest form of singleton detection is observed when all non-targets are homogeneous (e.g., all circles) rendering the target unique (e.g., Theeuwes, 1992). Our displays, however, contained multiple repetitions of three non-target shapes. This led to a slightly heterogeneous display with a target that was unique in form. It is plausible that either a feature or singleton search mode could have been adopted in response to these displays. Thus, there may have been a mix of participants who adopted feature or singleton search in the R-NT conditions, leading to the non-significant trends in the results mimicking the results of the feature search conditions (i.e., trending towards target activation and distractor inhibition). This could indicate the singleton search mode may be applied to a wider range of arrays than just the pure 'pop-out' search displays, even if a singleton-detection strategy is not perfectly efficient (Egeth et al., 2010). In Wang and Theeuwes' (2020) displays there were two singleton shapes. This would mean that a singleton search strategy would have been even less efficient than the current experiment (as both singleton shapes should have competed for initial attentional allocation). However, in both Wang and Theeuwes (2020) and the current experiment, results were consistent with a singleton search strategy being employed. This may speak to the relative ease of a singleton detection mode (as the target only would compete with one or two other items) over a feature-based search strategy in large set-size displays. While an exact search method for the R-NT search displays cannot be explicitly proven, it is clear is that the inhibition effect observed in the feature search conditions was not due to variations in distractor salience.

Past research showed that the observable inhibition effect is the combination of two separate mechanisms, the facilitation of target-relevant features and the suppression of the distractor feature (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022). The probe results from Experiment 1 indicated that both components were operating upon both the fully heterogenous and the mixed item search displays. The efficacy of target-feature enhancement should have been diluted in the larger search displays compared to smaller set size displays used in past studies (e.g., Chang & Egeth, 2019), as there were more feature-matching non-target items for the target to contend with. Yet, we were able to observe both target-feature enhancement and distractor-feature suppression in the ten-item search set size. Importantly, we were able to confirm these effects by assessing separate probe displays where the target and distractor feature values were compared against neutral baselines. This may explain differences between the current results and probe trials that compare both target-enhancement and distractor-suppression effects within in the same display (Oxner et al., 2023). That both target-feature enhancement and distractor-feature suppression appeared equivalent between the heterogeneous and R-NT search blocks is of some interest. This suggests that even though the inhibition effect was not observed in the search trials of the R-NT block, the distractor feature was still suppressed. This reveals that even when inhibition is unable to facilitate search, due to the current search mode or display properties, the repeated distractor features are still suppressed below baseline (e.g., Stilwell et al., 2024; Exp. 4, Wang & Theeuwes, 2020).

Authors' contributions ZHF: Conceptualization, methodology, investigation, original draft.

SIB: Conceptualization, supervision, review.

JP: Conceptualization, supervision, review.

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Data availability The data are available via the Open Science Framework at https://osf.io/vgcnq. The experiment was not preregistered.

Code availability Experimental code is available on request from ZHF.

Declarations

Ethics approval This study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Ethics approval for Experiment 1 was granted by the University of Queensland ethics committee (2020001300). For Experiment 2, approval was granted by the University of Toronto (42487).

Consent to participate All participants gave informed consent to participate in the study. All data was stored anonymously at the point of collection.

Consent for publication All participants gave informed consent for their (anonymised) data to be used in publication.

Conflicts of interest/Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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