

# Searching for Inefficiency in Visual Search

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## Abstract

■ The time required to find an object of interest in the visual field often increases as a function of the number of items present. This increase or inefficiency was originally interpreted as evidence for the serial allocation of attention to potential target items, but controversy has ensued for decades. We investigated this issue by recording ERPs from humans searching for a target in displays containing several differently colored items. Search inefficiency was ascribed not to serial search

but to the time required to selectively process the target once found. Additionally, less time was required for the target to “pop out” from the rest of the display when the color of the target repeated across trials. These findings indicate that task relevance can cause otherwise inconspicuous items to pop out and highlight the need for direct neurophysiological measures when investigating the causes of search inefficiency. ■

## INTRODUCTION

Visual search is said to be efficient or inefficient depending on whether or not additional time is required to find the target as the number of display items (set size) increases (Wolfe & Horowitz, 2004; Wolfe, 2003). In perfectly efficient search tasks, no additional search time is incurred by increasing the set size; in this case, the function relating RT to set size (herein called the *set-size function*) is flat. In very inefficient search tasks, RTs increase sharply as additional items are added to the display, with search slopes in excess of 30 msec per item (Pashler, 1999). Several theories of attentional selection have been proposed to explain these variations, but the causes of search efficiencies are not yet clear.

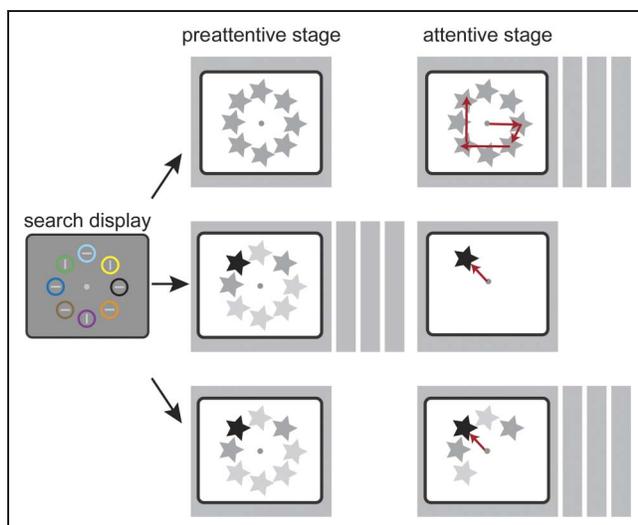
Search is hypothesized to involve two general stages of visual processing: an early, preattentive stage, in which items are processed in parallel and the saliency of these items is computed, and a later, attentive stage, in which items are selected individually for further analysis (Theeuwes, 2010; Itti & Koch, 2001; Desimone & Duncan, 1995; Wolfe, 1994; Treisman & Gelade, 1980; Neisser, 1967). According to this two-stage framework, efficient search occurs when the preattentively computed saliency of just one item—the target—is high enough to compete for attention. This is the case, for example, when the target is a feature singleton appearing in an array of identical distractors. The target attracts attention effortlessly in such situations; that is, it is said to “pop out” (Bravo & Nakayama, 1992). This type of search is often called “parallel search,” because processing at the early, parallel stage is sufficient to locate the target. If observers must

foveate or identify target, they may then deploy attention directly to its location (Bichot, Rossi, & Desimone, 2005). Set-size functions are often still flat in this latter type of search (herein called *direct search*), indicating that once the target pops out, it can be selected automatically (Bravo & Nakayama, 1992; Theeuwes, 1992).

Whereas flat set-size functions have been attributed to parallel search, positive set-size functions have most often been ascribed to “serial search” (Treisman & Gelade, 1980). Such inefficient searches can occur, for example, when the target shares similar visual features with the distractors or is defined by the absence of a specific feature (Treisman & Souther, 1985). In the context of the two-stage processing framework, the computed saliency of the target is no longer higher than that of any other display item, and in the absence of a strong bias toward the target, attention must be deployed serially to multiple items in the display until the target is found (Figure 1, top row).

Several lines of evidence illustrate that search can be direct or serial under different conditions. For example, when humans and monkeys are free to move their eyes during search for a feature-singleton target, they move their eyes directly to the target on the vast majority of trials (e.g., Ogawa & Komatsu, 2004; Bichot & Schall, 1999; Findlay, 1997). In contrast, when human observers must identify a subtle feature of a target in the presence of a very similar nontarget, they first shift attention to one of the items and then, if necessary, redeploy attention to the other item after 100 msec (Woodman & Luck, 1999, 2003). Although this latter pattern of results is consistent with serial search, it does not indicate that the positive search slopes obtained in more typical search tasks are because of multiple deployments of attention.

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**Figure 1.** Hypothetical causes of inefficient visual search for a green target in a multiple-singleton display. The broken, shaded region in each row highlights the stage at which processing is hypothesized to be inefficient. Top row: Serial search. Middle row: Inefficient preattentive processing. Bottom row: Inefficient attentive processing. See text for details.

In fact, the serial-search explanation for such positive slopes has faced stiff opposition. The general objection is that a positive set-size slope could arise from a variety of inefficiencies and thus does not provide unequivocal evidence for serial search (Townsend, 1990).

Figure 1 illustrates two alternative ways in which an increase in set size could lead to inefficient search. First, the presence of additional distractors might prolong the preattentive processes required to single out the target as the most salient item in the display (Figure 1, middle row). This would delay the subsequent deployment of attention but would not necessitate serial inspection of multiple items (Bichot & Schall, 1999; Folk & Remington, 1998). Second, the presence of additional distractors might prolong attentive processes required to resolve the target's identity, while leaving the duration of preattentive processes and the time at which attention is first deployed to the target unaffected (Figure 1, bottom row). Unfortunately, these alternatives and the conventional serial-search explanation all make similar predictions about the slope of the set-size function, thereby making it difficult for researchers to pinpoint the cause of inefficient search on the basis of behavioral data alone.

To address the possible sources of search inefficiency, we recorded ERPs from human observers performing a multiple singleton search task (Belopolsky & Awh, 2013; Anderson, Laurent, & Yantis, 2011). Participants searched for a red or green target that appeared among several heterogeneously colored distractors. Critically, this task pits against each other two factors that influence search performance in opposite ways: (i) distractor heterogeneity, which makes search less efficient, and (ii) target uniqueness, which makes search more efficient (Wolfe &

Horowitz, 2004). To uncover the sources of any search inefficiency, we measured the onset and amplitude of a neuroelectric component called the N2pc, which reflects attentional selection of an item in a visual search array (Gaspar & McDonald, 2014; Luck & Kappenman, 2012; Hickey, Di Lollo, & McDonald, 2009; Luck & Hillyard, 1994). In typical singleton search tasks, the N2pc emerges approximately 180–200 msec after the onset of the search display, regardless of set size (Mazza, Turatto, & Caramazza, 2009).

Target singletons can also elicit the N2pc when the display contains another nontarget singleton (Jannati, Gaspar, & McDonald, 2013; McDonald, Green, Jannati, & Di Lollo, 2013; Wykowska & Schubö, 2010; Luck & Hillyard, 1995). This latter finding suggests that the visual system can automatically select a task-relevant singleton even when it is no more salient than one other item in the visual field. In this study, we asked whether the visual system can select a target singleton when all of the display items are singletons, and thus, all items are nominally equal in salience.<sup>1</sup>

This study investigated the timing and amplitude of the N2pc as a function of set size (Experiment 1) and intertrial repetition (Experiment 2). Search performance was inefficient in Experiment 1, but the electrophysiological results showed that set size did not influence the timing of attentional deployment. Here, search inefficiency was linked not to serial search but to the duration of attentive processes required to select the target (selection time). The results of Experiment 2 showed that the target was attended sooner on color-repeat trials than on color-change trials—an effect known as priming of pop-out (Maljkovic & Nakayama, 1994). These results support the following conclusions: (i) task relevance can cause otherwise inconspicuous items to pop out, at least when those items possess unique attention-guiding features, and (ii) inefficiencies in search performance are not always caused by serial search.

## METHODS

The Office of Research Ethics at Simon Fraser University approved all experimental procedures.

### Experiment 1

#### Participants

Twenty-two observers participated in Experiment 1 after giving informed consent. Data from four participants were excluded from the analysis because >35% of the trials were rejected because of eye movements, blinking, or amplifier blocking, leaving 18 participants (eight men, mean age = 20.7 years, three left-handed) in the grand average. Ten different observers (four men, mean age = 19.6 years, one left-handed) participated in a control task (Experiment 1b) after giving informed consent. In both experiments, participants reported normal or

corrected-to-normal vision and were screened for color-blindness using Ishihara color plates.

### Apparatus

The experiment was conducted in a dimly lit, acoustically and electrically shielded chamber illuminated by DC-powered LED lighting. In Experiment 1, participants sat 57 cm from a computer monitor operating at a resolution of  $800 \times 600$  pixels and an 85-Hz vertical refresh. In Experiment 1b, participants sat 57 cm from an LCD monitor operating at a resolution of  $1920 \times 1080$  pixels and a 120-Hz refresh, the performance of which is suitable for both psychological testing and ERP time-locking (Lagroux, Yanko, & Spalek, 2012). Stimulus presentation was controlled by Presentation (Neurobehavioral Systems, Inc., Albany, CA) from a Windows-based computer. In Experiment 1, the EEG was recorded using custom software (Acquire) from a second Windows-based computer, using a 64-channel A-to-D board (PCI 6071e, National Instruments, Austin, TX) connected to a high input impedance EEG amplifier system (SA Instruments, San Diego, CA).

### Stimuli and Procedure

Search displays consisted of 4, 6, 8, or 10 items spaced equally around an imaginary circle ( $12.6^\circ$  radius) centered on a fixation point. The search array was presented for 2500 msec or until participants made a response. For the two largest set sizes, two items were located on the vertical meridian, one above and one below fixation. The items were colored, unfilled circles ( $2.2^\circ$  radius) containing lines of either a vertical or horizontal orientation ( $2.27 \times 0.4^\circ$ ). The background of the display was medium gray ( $18.5 \text{ cd/m}^2$ ), and the lines and fixation point were light gray ( $40.1 \text{ cd/m}^2$ ). The target was either a red ( $8.3 \text{ cd/m}^2$ ,  $u' = 0.59$ ,  $v' = 0.36$ ) or a green ( $25.9 \text{ cd/m}^2$ ,  $u' = 0.27$ ,  $v' = 0.61$ ) circle. In Experiment 1, only one of these target colors appeared on a given trial; in Experiment 2, half the trials contained either a red or a green target (each with 25% frequency), and half the trials contained neither a red or a green target. The colors of the distractor circles were selected at random from a set of either 9 (Experiment 1) or 10 (Experiment 1b) highly discriminable colors (cyan, yellow, black, orange, purple, brown, blue, magenta, white, and turquoise in Experiment 1b), such that no distractor color appeared more than once in the display.

Each trial began with a fixation point displayed for 500 msec, followed by the search display. The search display would remain visible for 2500 msec or until a response was registered. In Experiment 1, participants reported the orientation of the line inside the target circle by pressing one of two buttons on a standard computer mouse with the index and middle fingers of their

dominant hand. In Experiment 1b, participants were instructed to ignore the orientation of the line segments and to instead indicate the presence or absence of the red or green target. We required participants to search for one of two potential targets to maintain consistency with Experiment 2 (where two target colors were required) and with a previous study (Anderson et al., 2011). The number and color of the distractor circles varied pseudo-randomly across trials within each block so that each set size appeared 25% of the time. Orientation of the line contained within the target circle also varied pseudo-randomly. Participants received training on 48 practice trials and completed 25 blocks of 48 trials of the search task.

### Electrophysiological Recording and Analysis

EEG signals were recorded from 63 tin electrodes positioned at FP1, FPz, FP2, AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FC5, FC3, FC1, FCz, FC2, FC4, FC6, T7, C5, C3, C1, Cz, C2, C4, C6, T8, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, Iz, and M1 and five non-standard sites inferior to the standard occipital electrodes. All EEG signals were referenced to the right mastoid. EEG and EOG were amplified with a gain of 20,000 within a pass-band of 0.01–80 Hz and were digitized at 500 Hz. A semiautomatic procedure was performed to remove epochs of EEG that were contaminated by eye movements, blinks, and amplifier blocking. Artifact-free data were then used to create averaged ERP waveforms, which were digitally low-pass filtered ( $-3 \text{ dB}$  cutoff at 30 Hz) to remove high-frequency activity. The averaged event-related HEOG did not exceed  $2 \mu\text{V}$  for any individual participant, indicating that gaze remained within  $0.3^\circ$  of the fixation point for most trials (McDonald & Ward, 1999).

ERPs were computed separately for the 4-, 6-, 8-, and 10-item search arrays in which the target was presented in a lateral visual field and in which observers correctly evaluated the line segment within the target. ERPs were computed relative to a 100-msec prestimulus baseline. For each participant, the ERP waveforms were collapsed across left and right visual hemifields and left and right electrode sites to create waveforms recorded contralateral and ipsilateral to a lateral target. Lateralized ERP difference waveforms were then derived for each condition by subtracting the ipsilateral waveform from the corresponding contralateral waveform using lateral occipital electrode sites (PO7 and PO8). Negative voltages were plotted upward, such that the N2pc would appear as an upward deflection in these difference waveforms. The mean N2pc amplitude was computed from the contralateral-minus-ipsilateral difference wave in the 200–260 msec post-stimulus interval, and its onset latency was computed using a jackknife method as the point at which the difference waveform reached 50% of its peak amplitude in the 75–400 msec interval (Ulrich & Miller, 2001; Miller, Patterson, & Ulrich, 1998).

## Experiment 2

### Participants

Thirty-one new observers participated after providing informed consent. Data from five participants were excluded, leaving 26 participants in the grand average (11 men, mean age = 22.5, three left-handed).

### Apparatus

The apparatus was identical to that in Experiment 1b.

### Stimuli and Procedure

Stimuli were similar to those used in Experiment 1, with the exception that the display set size was fixed at eight items and no items were displayed on the vertical meridian. At the start of each trial, participants specified the color that was to be used for the target by pressing the green or red button on a gamepad (Logitech, Newark, CA). This was done to ensure that participants were always consciously aware of the color of the upcoming target. Participants were encouraged to follow an “RRGG” (or “GGRR”) pattern when specifying the target color. This was done to ensure roughly equal color-repeat and color-change trials. The search display appeared 800–1200 msec after participants selected the target color. Following the display onset, participants were asked to report the orientation of the line contained within the target circle by pressing one of two shoulder buttons on the game pad.

For one half of the experiment, participants searched for the red or green target among heterogeneously colored distractors (as in Experiment 1; multiple-singleton condition), and in the other half they searched for the target among homogenous distractors of the opposite color (i.e., red target among green distractors; green target among red distractors; one-singleton condition). Task order was varied across participants. Participants completed 14 blocks of 64 trials, for a total of 896 experimental trials, and participants completed 32 practice trials of both the multiple-singleton and feature-search conditions.

### Electrophysiological Recording and Analysis

EEG acquisition was as described for Experiment 1, with the exception that signals were instead recorded from 25 Ag/AgCl electrodes positioned at FP1, FPz, FP2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P7, P3, Pz, P4, P8, PO7, POz, PO8, O1, Oz, O2 and M1. ERPs were computed from artifact-free trials in which observers correctly evaluated the orientation of the line segment within the target. ERPs were computed separately for the multiple-singleton and one-singleton conditions and for trials in which the color of the target either repeated or changed. The method for analyzing the ERPs was as described in Experiment 1, except that the mean N2pc amplitudes were computed

in 50-msec intervals centered on the negative peaks in the contralateral-minus-ipsilateral difference waveforms for the four conditions. The mean amplitudes of the P1 and N1 were computed by averaging the contralateral and ipsilateral waveforms from 90 to 130 msec and from 160 to 200 msec poststimulus, respectively.

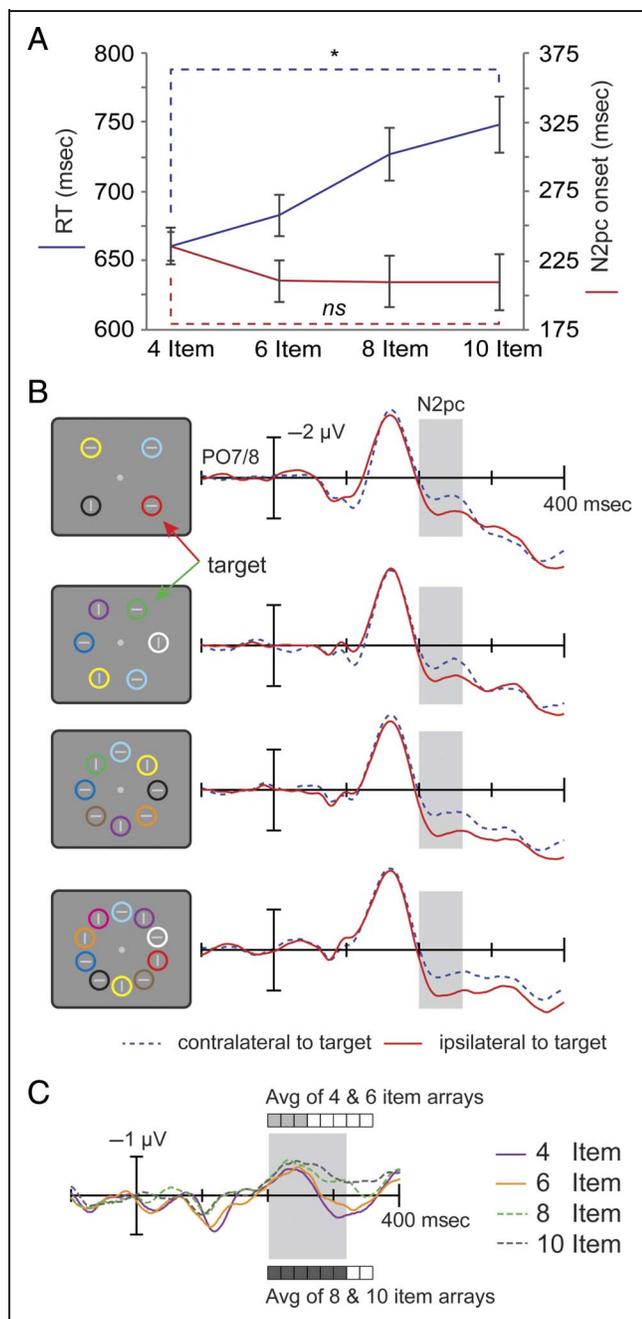
## RESULTS

### Experiment 1: Efficient Attentional Selection despite Inefficient Search Performance

Participants searched for a red or green circle (target) that appeared along with a varying number of differently colored circles (distractors; see Figure 1). Each circle contained a horizontal or vertical line segment, and participants were required to indicate the orientation of the line segment inside the target (i.e., compound search; Duncan, 1985). Because all circles were color singletons, the target was no more or less conspicuous than the distractors. Consequently, no item popped out from the rest of the array based on physical salience alone. The target’s uniqueness was still relatively high, however, because it possessed a unique color (a strong guiding visual attribute; Wolfe & Horowitz, 2004). Prior research indicates that participants may set themselves for a specific target feature under such conditions (called feature-search mode; Bacon & Egeth, 1994). Here, the hypothesized feature set would have to include both red and green because these different-colored targets were presented unpredictably across trials.

To assess the efficiency of search performance, we analyzed RT for correct response trials across the four set sizes using a one-way ANOVA (after excluding 12.8% of trials because of oculomotor artifact). RTs were found to increase with set size,  $F(3, 51) = 54.50, p < .001$ . The slope of RT  $\times$  Set size function was 15 msec per item (Figure 2A), which is similar to the slopes obtained in other multiple-singleton search tasks (Theeuwes, 2004; Bacon & Egeth, 1994). Observers also committed more errors as set size increased,  $F(3, 51) = 4.39, p = .008$ , indicating that a speed–accuracy trade-off did not occur (Table 1). These results indicate that search performance was moderately inefficient.

To ensure that that the positive set-size slope was not caused by the use of a compound search task, we collected RTs in a detection variant of this multiple singleton search task (Experiment 1b). This control experiment was similar to Experiment 1, except that displays contained a target (green or red circle) on only 50% of the trials. Participants were instructed to determine whether one of the targets was present or whether both were absent. As in Experiment 1, RTs increased with set size,  $F(3, 27) = 47.91, p < .001$ . Participants were also faster to respond on target-absent trials than on target-present trials,  $F(1, 9) = 24.44, p < .001$ . Critically, on target-present trials, the slope of the set size function in this detection task (12 msec/item) was not significantly different than



**Figure 2.** Experimental task and main results for Experiment 1. (A) Mean RT increased with larger set sizes (15 msec/item), but the onset of the N2pc remained constant regardless of set size. (B) Grand-averaged ERPs elicited by the 4-, 6-, 8-, and 10-item search displays. The target (red or green circle) elicited an N2pc in all conditions. (C) Contralateral–ipsilateral difference waveforms based on the ERPs shown in B. The difference waves were constructed such that the N2pc is seen as an upward (negative) peak. There was no significant difference in the onset or magnitude of the N2pc across the four set sizes, but the duration of the N2pc was significantly longer for the two larger set sizes than for the two smaller set sizes.

that obtained in the main, compound search task,  $t(26) = 1.04, p = .31$ . Thus, the inefficiency in search performance cannot be ascribed to the usage of a compound search task.

The hypotheses illustrated in Figure 1 lead to contrasting predictions about how an increase in set size would influence the target-elicited N2pc in Experiment 1. First, if search is serial and unguided (Figure 1, top row), little or no N2pc would be observed in the ERP waveform after averaging all trials. This is because an unguided serial search would trigger multiple, successive N2pc waves on each trial—that is, a different N2pc would be triggered each time attention was focused on a different item (Woodman & Luck, 1999, 2003). Critically, the N2pc waves elicited when attention is deployed to items in the non-target hemifield would counteract the N2pc waves elicited when attention is deployed to items in the target hemifield, leaving no overall N2pc in the averaged ERP waveform. Second, if an increase in set size prolongs processing at the early, parallel stage but does not impair direct search (Figure 1, middle row), an increase in set size would delay the onset of the target N2pc but would not otherwise influence N2pc amplitude or duration (Wykowska & Schubö, 2011). Third, if an increase in set size prolongs processing involved in selecting the target but does not influence early, parallel processing or the time at which target selection begins (Figure 1, bottom row), an increase in set size would prolong the duration of the target N2pc without delaying its onset. Finally, if multiple singleton search is completely efficient at least until the selection stage has been completed, increasing set size would have no effect on search performance or the target N2pc waveform.

Analysis of the ERP waveforms elicited by the different-sized search arrays revealed four key results (Figure 2B). First, the N2pc was in evidence for all four set sizes, disconfirming the purely serial-search explanation. The amplitude of the N2pc differed significantly from zero in the 200–260 msec interval (all  $t_s > 2.35$ , all  $p_s < .031$ ).

**Table 1.** Median Correct RTs and Error Rates by Experimental Condition

Experiment/Condition	Median RT (SEM) msec	Error Rate (SEM) %
<i>Experiment 1</i>		
4-item	660 (13.5)	5.1 (0.7)
6-item	683 (14.9)	6.1 (0.9)
8-item	727 (18.9)	7.5 (1.0)
10-item	748 (20.4)	7.4 (1.1)
<i>Experiment 2</i>		
Multiple singleton, color repeat	761 (18.4)	5.2 (1.2)
Multiple singleton, color change	882 (27.8)	8.0 (1.5)
Feature search, color repeat	685 (14.4)	3.3 (0.5)
Feature search, color change	773 (21.3)	4.4 (0.9)

Second, the amplitudes and onset latencies of the N2pc waves were found to be statistically indistinguishable across the four set sizes,  $F_s < 1$ . Critically, the set-size function for N2pc onset latency was flat (numerically:  $-4$  msec/item; Figure 2A). Thus, despite the behavioral evidence for inefficient search, these electrophysiological results indicate that the target popped out at the level of attentional selection. Third, although the onset latency of the N2pc was invariant, the duration of the N2pc varied as a function of set size. For the N2pc duration analysis, new waveforms were computed by averaging the contralateral-minus-ipsilateral difference waveforms of the two smaller arrays and the two larger arrays. The resultant waveforms (not shown) were then  $t$  tested against zero, in 20-msec intervals, from 200 to 360 msec (dark gray boxes on the abscissa in Figure 2C). This analysis confirmed that the duration of the N2pc was significantly longer for the large arrays (200–320 msec) than for the small arrays (200–260 msec). A paired-samples  $t$  test also revealed that the N2pc was more negative for the two large arrays in the 260–320 msec interval,  $t(17) = 2.74, p = .014$ .

The fourth major ERP result was that, for the two smaller set sizes, a contralateral positivity was present in the 125–150 msec interval. This posterior, contralateral positivity (Ppc) is typically observed when a singleton target is presented among homogenous distractors and has been hypothesized to reflect bottom-up salience (Jannati et al., 2013; Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012). In this study, the Ppc was found to differ significantly between set sizes,  $F(3, 51) = 3.76, p = .016$ . A post hoc  $t$  test revealed that the Ppc was significantly larger for the two smaller arrays (averaged together) than the two larger arrays,  $t(17) = 2.91, p = .010$ .

In summary, the ERP results from Experiment 1 indicate the following: (i) processing at the early, parallel stage was efficient; (ii) attention was deployed directly to the target in the same amount of time for 4-, 6-, 8-, and 10-item arrays; (iii) attentional selection was prolonged for larger displays. In other words, the search inefficiency in this task is attributable to increased attentional selection time.

### Experiment 2: Intertrial Priming of Pop-out Facilitates Multiple-singleton Search

Experiment 1 showed that the timing of the preattentive stage of processing is not affected by display set size. This is consistent with the hypothesis depicted in the bottom row of Figure 1, in which search inefficiency is linked to an increase in the duration of the attentive stage. Experiment 2 was performed to further understand this particular processing stream. Specifically, we sought to determine if the timing of either the preattentive or attentive stages could be influenced by selection history.

Previous studies have shown that the repetition of a target's features from one trial to the next facilitates

search for a singleton under typical pop-out conditions (i.e., when one salient singleton appears among a homogeneous set of nontargets; Maljkovic & Nakayama, 1994). It has been hypothesized that this intertrial priming of pop-out occurs because selection of the target features on trial  $n$  biases the visual system toward selection of those same features on trial  $n + 1$  (Awh, Belopolsky, & Theeuwes, 2012). This biasing is thought to occur via facilitation of the preattentive stage of processing (Lee, Mozer, & Vecera, 2009). Consistent with this interpretation, intertrial priming leads to an earlier N2pc, indicating that target singletons are selected sooner when their features repeat across successive trials than when their features change, at least when the target is set against an array of homogenous distractors (Eimer, Kiss, & Cheung, 2010).

In Experiment 2, we sought to determine if intertrial priming would facilitate target selection in the multiple-singleton search task. In other words, we asked whether priming of pop-out would facilitate selection of the target, even when none of the items popped out on the basis of bottom-up salience. Here, participants searched for a red or green target in a fixed array of eight items. On each trial, participants selected the color of the upcoming target by pressing either a green or a red button on a standard computer gamepad. Participants were instructed to follow an "RRGG" (or "GGRR") pattern to ensure an equal number of color-repeat and color-change trials. This was done to ensure that participants knew the color of the upcoming target. In one half of the experiment, the target was presented among heterogeneously colored distractors, as in Experiment 1. We refer to this as the multiple-singleton condition. In the other half of the experiment, the target was presented among homogenous distractors of the opposite color (i.e., a red target among green distractors or vice versa). We refer to this as the one-singleton condition.

In all, 16.5% of trials were excluded because of oculomotor artifact. Participants responded correctly on 94.8% of the remaining trials. Behavioral and electrophysiological effects were quantified based on target type (color repeat vs. color change) and condition (multiple singleton vs. one singleton). Consistent with the priming of pop-out effect, RTs were faster on color-repeat trials than on color-change trials,  $F(1, 25) = 106.29, p < .001$ . The magnitude of this priming was larger in the multiple-singleton condition (122 msec) than in the one-singleton condition (88 msec), as evidenced by a significant Target type  $\times$  Condition interaction,  $F(1, 25) = 8.72, p = .007$ . Participants also committed more errors on target change trials,  $F(1, 25) = 16.83, p < .001$ , indicating that a speed-accuracy tradeoff did not occur (Table 1).

Figure 3A displays contralateral-minus-ipsilateral difference waves obtained in the two conditions, collapsed over color-repeat and color-change trials. Each waveform contained a prominent N2pc in the same general time range, beginning  $\sim 200$  msec poststimulus and lasting until

approximately 320 msec. Statistical analysis revealed that the N2pc onset latency for the multiple-singleton condition (222 msec) did not differ from that of the one-singleton condition (213 msec),  $t_{\text{corrected}}(25) = 1.54$ ,  $p = .14$ . To assess N2pc duration, we again computed mean amplitudes in consecutive 20-msec intervals from 200 to 360 msec (dark gray boxes on the abscissa in Figure 3A). Each N2pc was found to be significant until 300-msec post-stimulus. These analyses indicate that the timing of the N2pc was very similar across the two conditions. By contrast, mean N2pc amplitude was found to be significantly larger for the multiple-singleton condition than in the one-singleton condition in the 225–275 msec interval,  $t(25) = 2.76$ ,  $p = .011$ . Given that N2pc amplitude has been linked to selection difficulty (Luck, Girelli, McDermott, & Ford, 1997), these results indicate that it took more effort to filter out the differently colored distractors than the uniformly colored distractors.

Figure 3 (B and C) presents the difference waveforms obtained on color-repeat and color-change trials. Critically, the onset of the N2pc was earlier on color-repeat trials (206 msec) than on color-change trials (228 msec),  $F_{\text{corrected}}(1, 25) = 29.91$ ,  $p < .001$ , confirming that priming of pop-out facilitated attentional selection of the target. The onset of the N2pc was unaffected by condition, and the Condition  $\times$  Target type interaction was nonsignificant. These results indicate that the heterogeneity of distractor color had no influence on the magnitude of the intertrial priming of pop-out.

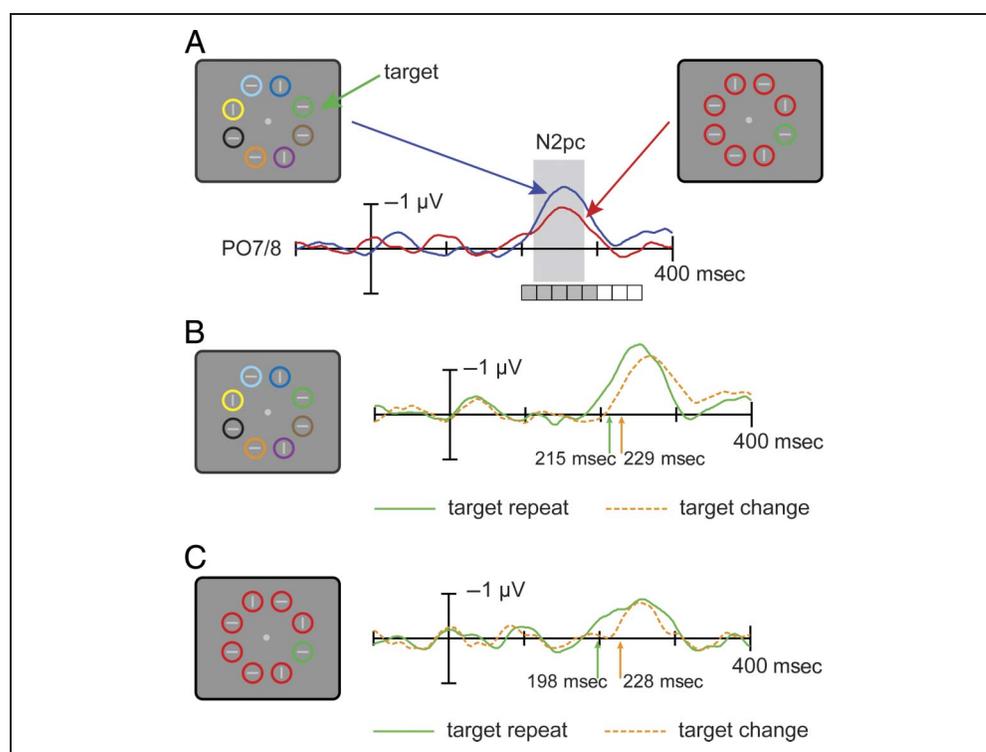
Whereas intertrial priming influenced the timing of N2pc onset, it did not appear to influence N2pc amplitude, which

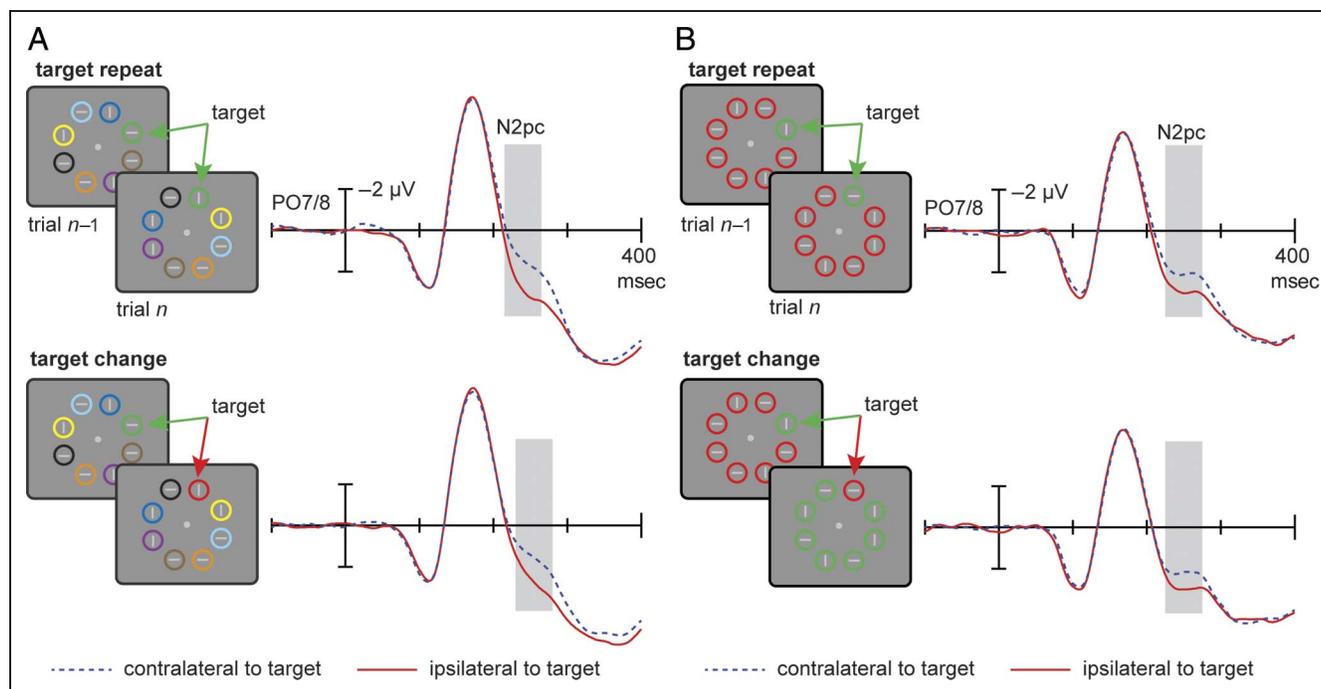
was statistically indistinguishable on color-repeat and color-change trials (the Target type  $\times$  Condition interaction was also nonsignificant). These results indicate that, although target selection was delayed on color-change trials, selection was no more difficult when target color changed from one trial to the next than when it repeated across successive trials.

So far, the earliest effect of priming appeared to be a 22-msec shift in N2pc onset latency (see also Eimer et al., 2010). To determine whether this was indeed the earliest effect, we measured the amplitudes of the P1 and N1 components of the ERP waveforms recorded contralateral and ipsilateral to the target in each condition (Figure 4). The P1 and N1 amplitudes were found to differ across search conditions: The P1 was larger in the one-singleton condition (2.01  $\mu\text{V}$ ) than in the multiple-singleton condition (1.62  $\mu\text{V}$ ),  $F(1, 25) = 9.50$ ,  $p = .005$ , whereas the N1 was larger in the multiple-singleton condition ( $-5.24 \mu\text{V}$ ) than in the one-singleton condition ( $-4.80 \mu\text{V}$ ),  $F(1, 25) = 11.06$ ,  $p = .003$ . Critically, each of these early sensory-evoked ERP components was similar in amplitude for color-repeat and color-change trials, all  $F$ s  $< 1$ , confirming that the earliest electrophysiological cost of a color change occurred in the interval of the N2pc.

In summary, Experiments 1 and 2 provide converging evidence that the task-relevant target contained in multiple-singleton search displays does in fact pop out at the level of preattentive processing. As a result, the target can be found by direct attentional selection and does not require serial deployments of attention—despite the positive set size slope observed in Experiment 1, a

**Figure 3.** Experimental task and electrophysiological results for Experiment 2. (A) Ipsilateral-minus-contralateral difference waveforms for the multiple-singleton (blue) and one-singleton (red) conditions. The amplitude of the N2pc was larger for the multiple-singleton condition; however, neither the onset nor the duration of the N2pc differed between conditions (gray boxes on abscissa). Difference waveforms in (B) the multiple-singleton condition and (C) the one-singleton condition when the color of the target repeated (green) or changed (orange dashed) trials. For both conditions, the N2pc was earlier on color-repeat trials but did not differ in amplitude.





**Figure 4.** Electrophysiological results from Experiment 2 for (A) the multiple-singleton condition and (B) the one-singleton condition. In both conditions, the amplitudes of the P1 and N1 components were not significantly different when the color of the target repeated (top row) relative to when the color of the target changed (bottom row).

result that has frequently been used to infer seriality of processing.

## DISCUSSION

For several decades, researchers have examined how set size affects search performance to determine whether search in any given task is efficient or inefficient. Traditionally, efficient and inefficient patterns of performance were associated with parallel search and serial search, respectively. More recently, researchers have conceptualized a continuum of inefficiency rather than a strict dichotomy between efficient and inefficient search tasks (Wolfe, 1998), but the underlying neural causes of inefficiency are still largely unknown. Here, we used the ERP method to uncover the cause of inefficiency in a multiple singleton search task. Performance was found to be moderately inefficient when set size was varied (Experiment 1). Although such inefficient performance has been attributed to serial inspection of multiple items (Theeuwes, 2010; Treisman & Souther, 1985; Treisman & Gelade, 1980), the ERP results obtained in this study showed that attention was deployed directly to the target, regardless of the number of items in the display. Search inefficiency was attributed not to serial search but to increased attentional selection time for displays containing more distractors.

In Experiment 1, set size modulated the duration of the N2pc but not the onset latency or amplitude of the N2pc. At first glance, the absence of an N2pc amplitude

effect appears to be at odds with previous studies in which N2pc amplitudes increased as set size increased (Mazza et al., 2009; Luck et al., 1997). It is likely that this apparent discrepancy is because of the contrasting way in which set size was increased: In previous studies, set size was increased by adding identical nontarget items to the display, whereas in the current study, set size was increased by adding unique nontarget items to the display. In the former case, the target may have been easier to find when set sizes were large because of the enhanced gradient discontinuity provided by the more uniform background (nontarget) items. Such enhanced gradient discontinuities are often associated with negative—rather than positive—search slopes: RTs actually get shorter as set size increases (Bravo & Nakayama, 1992). Mazza et al. (2009) did observe negative search slopes in some of their search conditions, indicating that the target was indeed easier to find when the set size was increased. In contrast, the gradient discontinuity would be minimal in this study because the target appeared on a heterogeneous array of nontarget singletons regardless of set size. On this basis, we suspect that the set-size effects on N2pc amplitudes observed in previous studies may have been related to the increased ease with which the target could be located.

In the context of visual search, “pop-out” is said to occur when one item can be differentiated from other items in the search array effortlessly. The term is usually associated with singleton search tasks in which target uniqueness is maximized and distractor heterogeneity is minimized. Contemporary models of visual search ascribe

pop-out to physical factors that boost stimulus salience (e.g., local contrast; see Theeuwes, 2010; Wolfe & Horowitz, 2004; Itti & Koch, 2001). By this account, an item that is physically dissimilar to neighboring items pops out. Such bottom-up pop-out cannot occur in the multiple-singleton search task because all items are distinct, and thus, no one item captures attention on the basis of its physical uniqueness. Still, the ERP results of Experiment 1 were consistent with efficient search. On this basis, we conclude that making one of many singletons relevant causes that item to pop out although it is no more salient than its neighbors. This conclusion is consistent with models of visual search that permit top-down attentional guidance. For example, the guided-search model (GS4) proposes that a match between a display item and the attributes of the stored target representation can lead to efficient search (Wolfe, 2007).

The pop-out that occurred in Experiment 1 was found to be susceptible to intertrial priming in Experiment 2. Typically, this intertrial priming is observed with conventional pop-out displays containing a singleton target set against an array of homogenous distractors. The results from this study show that intertrial priming of pop-out extends to inconspicuous objects made salient by task relevance, at least when the target possesses a unique guiding feature. Beyond this main finding, two aspects of the results are worth noting here. First, the priming effects were in evidence, although participants determined the color of the target on every trial. That is, knowledge of the upcoming target color did not eliminate the cost of switching target color. This is in line with the conclusion that priming of pop-out is reflexive and cognitively impenetrable (Maljkovic & Nakayama, 1994). Second, the difference in N2pc onset latency (~200–230 msec) was the earliest difference between the ERPs on color-repeat and color-change trials. There was no difference in amplitude or latency of the earlier P1 or N1 components. This is in line with the conclusion that, although priming of pop-out facilitates the deployment of attention to repeated features, it does not enhance earlier perceptual-level processing of those features (Lee et al., 2009).

The present results highlight the utility of the ERP method in determining the exact origin of search inefficiency. It has been proposed—and it is generally well accepted among researchers—that an item possessing a unique color can strongly guide attention toward its location (Wolfe & Horowitz, 2004). The means by which such strong guiding attributes affect attentional deployment is unclear, however. Here, the ERP results establish that, in the presence of a strong guiding feature, search inefficiency was minimal and was linked specifically to selection times. This result contrasts with a pair of recent ERP studies in which search inefficiency was instead linked to the preattentive stage when the target was defined by a weaker guiding attribute. Specifically, N2pc latency was found to increase with set size when the task was to search for a form singleton or for a target defined by a conjunction of features (Wolber & Wascher, 2003, 2005). This pattern of

results is perfectly in line with the prediction stemming from our own preattentive-inefficiency hypothesis (see Figure 1, middle row). Finally, results of another recent study suggest that search can be serial when the target is defined by the absence of a feature, at least when search displays are very brief and set size varies randomly across trials (Dowdall, Luczak, & Tata, 2012, Experiment 1). When averaged across all trials, the ERPs contained no hint of N2pc in this case. This latter finding is in line with the prediction stemming from the serial-search hypothesis (see Figure 1, top row). Search thus becomes serial when there is no feature that can be used to guide attention toward the target.

The challenge in determining the cause of inefficient search based on RTs alone is also highlighted in a debate about the deployment of attention in multiple-singleton search tasks. In these tasks, the target is defined by a unique feature (a singleton), but some or all of the distractors are also singletons (as in Experiment 1). Because the target is not the only unique item, observers cannot reliably locate it by detecting a discontinuity in the search array. Instead, observers must set themselves to search for the defining feature of the target (feature search mode). The adoption of a feature-search mode leads to relatively inefficient search performance, as evidenced by a positive search slope in the 10–15 msec/item range. On the basis of this moderate slope, some researchers proposed that this feature search mode requires serial deployments of attention (Theeuwes, 2004), whereas others proposed it can be performed entirely in parallel (Bacon & Egeth, 1994). The approach used in this study avoids such dichotomization by addressing inefficiencies at various stages of processing. The present findings are inconsistent with a purely serial mechanism underlying color-based feature search mode, but the increased selection time observed in Experiment 1 shows that search in this task is not perfectly efficient.

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### Note

1. A singleton is an item that possesses one attribute that sets it apart from all other items (Egeth & Yantis, 1997). Although this term is typically used when just one item possesses a unique feature and the remaining items are all identical, we use the term to refer to any stimulus that possesses a unique feature. By this definition, visual search displays can contain just one singleton (typical feature search tasks), two singletons (e.g., the additional singleton paradigm; Theeuwes, 2010), or several singletons (Theeuwes, 2004; Bacon & Egeth, 1994).

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