

## The “red-alert” effect in visual search: Evidence from human electrophysiology

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### Abstract

Participants had to determine the orientation of a segment inside a target color circle among other gray distractor circles. The target circle was either red or green and was accompanied in the display by a distractor in the other color. To dissociate event-related potentials of target and distractor processing, one of them was on the vertical meridian and the other in a lateral position. In Experiment 1, the target color was indicated on a per-trial basis and, in Experiment 2, on a per-block basis. The results revealed the N2pc elicited by red targets had an earlier latency relative to the N2pc elicited by green targets. Contralateral responses of positive polarity linked to distractor inhibition were found only with red lateral distractors. The results suggest that the choice of colors to distinguish targets from distractors may play a role in visual search performance and in the functional characterization of event-related lateralizations.

**Descriptors:** EEG/ERP, Visual attention, N2pc, P<sub>D</sub>, Colors

Current views on how task-relevant information is selected from scenes including potentially distracting information agree that two complementary mechanisms operate to achieve this goal. Target information activation is held to be enhanced while distracting information is concomitantly suppressed (e.g., Desimone & Duncan, 1995). Over the past two decades, this synergistic interplay between facilitatory and inhibitory mechanisms has received support from event-related potential (ERP) studies focusing on visual search. These studies have revealed that lateral targets elicit an increase in negativity over the contralateral posterior hemisphere usually unfolding in a 180–280 ms time window, termed N2pc, and usually measured under conditions in which an equivalent distractor is present in the visual hemifield opposite to that occupied by the target (Eimer, 1996; Jolicœur, Brisson, & Robitaille, 2008; Luck & Hillyard, 1994; Robitaille & Jolicœur, 2006; Woodman & Luck, 2003). An elegantly simple experimental design often employed to track processing taking place during target search involves presenting two lateral items, one to the left and one to the right of fixation, and monitoring the amplitude and latency of the N2pc response as a function of a variety of experimental manipulations (e.g., Dell’Acqua, Sessa, Jolicœur, & Robitaille, 2006; Eimer, 1996; Jolicœur, Sessa, Dell’Acqua, & Robitaille, 2006a, 2006b). One limitation of this approach is that it is difficult to distinguish activity related to processing of the target and distractor(s) in the ensuing N2pc. The N2pc waveform is calculated by subtracting from the activity measured on the scalp at contralateral electrode sites relative to the target the activity meas-

ured at corresponding ipsilateral electrode sites, thus potentially conflating brain activity elicited by all lateral items (i.e., target on one side and distractor on the other) in the visual search display into a single component.

In an elegant inversion of the logic of examining lateralized brain activity in response to lateral stimuli, Woodman and Luck (2003) isolated activity of a lateral stimulus from another salient stimulus by presenting this latter item on the vertical meridian. The item on the vertical meridian is both in the left and the right visual hemifield, and so it cannot produce a systematic brain lateralization as a function of the position of another lateral item presented sometimes in the left and sometimes in the right visual field, thereby nullifying any systematic lateralization of brain activity of the item on the vertical meridian. Hickey, Di Lollo, and McDonald (2009) used the method introduced by Woodman and Luck (2003) in search displays in which one stimulus was a lateral item and one was placed eccentrically along the vertical meridian. When the lateral item was a target, event-related lateralizations (ERLs) showed a component similar to the N2pc, which they named N<sub>T</sub> (negativity related to the target). When the lateral item was a distractor, the ERLs showed a positivity between 230 ms and 280 ms after the presentation of the search display, contralateral to the lateral distractor, which was termed P<sub>D</sub> (positivity related to the distractor). They hypothesized that the P<sub>D</sub> component reflected a process of distractor suppression. Sawaki and Luck (2010) also found a positivity related to a distractor, but in a much earlier time window, namely between 115 ms and 225 ms. The difference in timing between Hickey’s and Sawaki’s distractor-induced positive reactions could perhaps be explained by differences in the experimental paradigms, but could also reflect a different process altogether. Whereas Hickey et al.’s (2009) arguments were based on a distractor that was always a red line that had been adjusted to match

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the subjective brightness of the background, Sawaki and Luck (2010) used displays containing a salient uniquely colored lateral distractor, either green or red. The latency of the  $P_D$  as well as the experimental condition in the Sawaki and Luck (2010) experiments would tend to suggest the component is a positive posterior contralateral component (Ppc), which has been linked to a sensory imbalance in the physical structure of search displays (Corriveau et al., 2012; Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012; Leblanc, Prime, & Jolicœur, 2008). The salience and color differences between Hickey's and Sawaki's experimental paradigms could have caused the differences observed across experiments in terms of contralateral positive deflections.

On the other hand, while examining the potential causes of this temporal discrepancy between the two mentioned studies, we noted that a systematic ERP investigation of the role of color in modulating lateralized ERP responses in visual search, at least to our knowledge, has never been conducted as of yet. Color is well known as a privileged feature facilitating the attentional processing of a visual stimuli (Wolfe, 2000; Wright, 1972), and there is a vast psychophysical and visual search literature, but reports of chromatic attentional effects (color-to-color) in other paradigms and on lateralized ERP components are scarce. A flanker task experiment (McCarley & Mounts, 2008) raised the question that color-specific bias, for equiluminant colors, could play a role in attentional processing when they showed a stronger interference in a green-red target-flanker pair when the flanker was red. Exploring whether a class of attention-modulated ERP responses in visual search are bound to the choice of specific colors (or differences in color between targets and distractors) is of obvious importance, as it may lead to revisit claims on the functional characterization of ERP (sub)components in the N2 range that largely prescinded, in their original formulations, considerations of this physical dimension.

Examining the electrophysiological manifestations of attentional control, selection of targets, and suppression of distractors, while also examining the potential impact of specific colors chosen for target/distractor is the aim of the present investigation. As done by Hickey et al. (2009), we placed one colored item (e.g., red) on the vertical meridian and one item of a different color (e.g., green) in a lateral position, in a display otherwise composed of gray distractors, as illustrated in Figure 1. All of these stimuli had the same luminance, which equated the overall luminance afferent stimulation from each visual hemifield. Luminance was equated using a Minolta CS100 chromameter. We found, in concurrent work, that the adjustments based on this instrument match those found by psychophysical adjustments based on heterochromatic

flicker photometry (Shioiri & Cavanagh, 1992). As shown in Figure 1, all of our stimuli were more luminous than the background, and the luminance adjustments of the red, green, and gray stimuli ensured that the sensory inputs from the two hemifields were approximately equal. We note that the procedure used by Hickey et al. (2009) was different. They asked participants to adjust the subjective brightness of a red stimulus to match the brightness of the background (both low intensity), and they also used a much brighter green stimulus. They dealt with associated afferent differences between hemifields by experimentally manipulating which stimuli were to be attended or ignored via task relevance, which was a reasonable approach. We prefer to equate luminance rather than subjective brightness because luminance is closely linked to underlying neurophysiological channels in the visual system, which we are trying to equate across visual fields, and correlates better with achromatic form perception than brightness (Shioiri & Cavanagh, 1992).

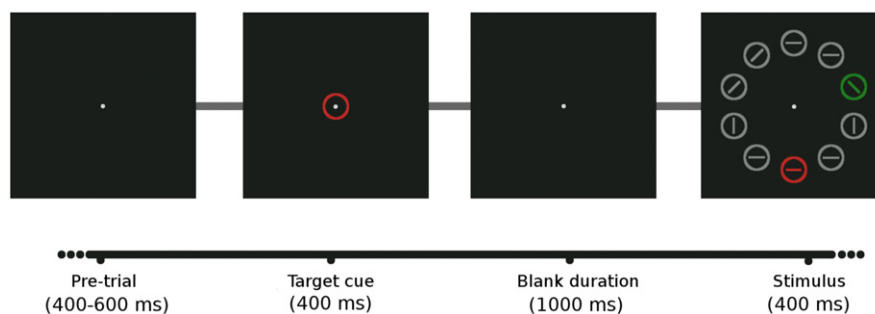
## Experiment 1

### Method

**Participants.** Twenty-five participants completed Experiment 1 voluntarily and received monetary compensation in an experiment vetted by the Ethics Committee of the Faculty of Arts and Science at Université de Montréal. They had normal or corrected-to-normal vision, were neurologically normal, and were not taking neurologically active medication according to self-reports. Data from 20 were kept for analysis (15 women) with a mean age of 23.1 (19 to 30 years old). Among the rejected participants, four were rejected due to excessive eye blinks and eye movements toward a lateral item, and one participant was rejected due to near-chance accuracy (criterion described in the Recordings section).

**Stimuli.** An example of the stimuli and trial design in Experiment 1 are illustrated in Figure 1.

Two types of displays were used. The cue display was a single colored circle around the gray fixation dot indicating the target color for the current trial. The search display consisted of 10 nearly equiluminant circles (red:  $11.1 \pm 0.1$  cd/m<sup>2</sup>,  $x = .629$ ,  $y = .345$ ; green:  $11.2 \pm 0.1$  cd/m<sup>2</sup>,  $x = .303$ ,  $y = .591$ ; gray:  $10.9 \pm 0.1$  cd/m<sup>2</sup>,  $x = .264$ ,  $y = .312$ ) evenly distributed along an imaginary circle (8° of diameter) centered at fixation. Each circle had a diameter of 1.5° of visual angle. The uppermost and lowermost circles were on the vertical meridian, and two circles were



**Figure 1.** Timecourse of Experiment 1 and 2 display presentations. The lateral colored item can be either a target or distractor, and the target color was displayed in the cue presented around the fixation point early in the trial. In Experiment 2, the target color was blocked so the cue presented before the search display was the same during a block, whereas in Experiment 1 it changed pseudorandomly trial by trial.

positioned in each quadrant, with no circle on the horizontal meridian. Each circle contained a line with a length of  $0.9^\circ$  of visual angle at one of four possible orientations (horizontal, vertical,  $45^\circ$  tilted to the left oblique, or  $45^\circ$  tilted to the right). All circles were gray with the exception of two circles, one red and one green. The positions of the red and green circles were varied from trial to trial, but in each display one colored circle was in one of the two vertical meridian positions while the other was lateral. The lateral colored circle was always at a distance of 3 positions (2 intercalated items) from the vertical meridian colored circle. The stimuli were presented in a dimly lit room on a Viewsonic P75f+ cathodic monitor.

**Design and procedure.** Each trial started with the presentation of a fixation point. The fixation point remained visible throughout the trial until a feedback was presented at the end of the trial. A 400-ms color-cue display was presented 400–600 ms after the space bar press. The target/distractor color mapping was determined at run time, and with equal probability. A 1,000-ms blank interval followed the offset of the color-cue display. The search display then appeared until a response was detected, or 3,000 ms had elapsed. The participant had to indicate, as quickly and accurately as possible, the orientation of the bar inside the target-color circle (i.e., the circle of the same color as the color-cue), disregarding all other items in the search display, by pressing one of four response keys. Response hand was counterbalanced across participants. Participants instructed to use their left hand used the {x, c, v, b} keys, whereas participants instructed to use their right hand used the {n, m, , (comma), . (period)} keys on a North American QWERTY keyboard, each key corresponding to one line orientation {tilted to the left, vertical, horizontal, tilted to the right, respectively}. Feedback on response accuracy was shown at fixation (+ or – signs) at the end of the trial for 500 ms. Participants completed 1 block of 32 practice trials followed by 8 blocks of 128 experimental trials.

**EEG recordings and analysis.** The electroencephalogram (EEG) was recorded with 64 active scalp Ag/AgCl electrodes (BioSemi ActiveTwo system) mounted on an elastic cap. Positioning and naming of the electrodes followed the International 10-10 system (Sharbrough et al., 1991). Data were digitized at a sampling rate of 256 Hz, low-pass filtered online at 67 Hz, and band-pass filtered offline between 0.05 and 20 Hz in postrecording analyses. Trials with a correct response were segmented, time-locked to the onset of the search display, from 200 ms prior to display onset to 600 ms after (800 ms total). These segments were averaged and baseline corrected based on the mean activity during the 200-ms prestimulus period. The horizontal electrooculogram (HEOG) was recorded and computed as the difference between signals at two additional electrodes located on the external canthi of each eye. The vertical electrooculogram (VEOG) was recorded and computed as the difference between signals at an electrode located above (FP1) and an additional electrode below the left eye. Two additional electrodes were used to record signals at the left and right mastoids, and all signals were referenced in postrecording analysis to the average of the voltage at the mastoids. Trials with blinks were rejected based on VEOG variations of more than  $50 \mu\text{V}$  in a 200-ms time window scrolled throughout each trial segment duration. Trials with horizontal eye movements, defined as HEOG variations larger than  $40 \mu\text{V}$  in a 200-ms time window scrolled through each trial segment, were rejected. We rejected data from participants who had less than 50% of trials retained after removing incorrect responses and trials with blinks or eye movements when trials were split across experimental conditions.

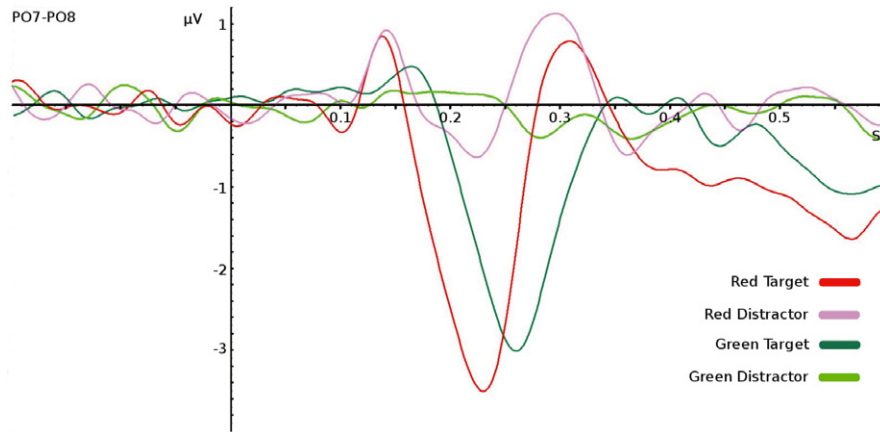
Component amplitude measures for statistical analysis were obtained by averaging the time-point measurements over a time period surrounding a period of interest for each electrode. This period of interest was centered on the time of peak amplitude for the grand-averaged waveform across participants, for a particular component. When no discernible component could be seen, the time of peak amplitude from a corresponding condition was used instead. The width of the averaging period was set to 50 ms for the N2pc, and 30 ms for the shorter Ppc and P<sub>D</sub> components. The latency statistics on the N2pc were evaluated using the jackknife technique. The jackknife method is based on the computation of N jackknife grand averages where each average is based on N-1 participants, removing each participant from one of the averages. The latency at which the N2pc in each of these jackknife grand-averaged waveforms reached an amplitude of  $-1 \mu\text{V}$  was measured and submitted to an analysis of variance (ANOVA) corrected by dividing the calculated *F* by (N-1)<sup>2</sup> to correct for the reduced error variance of estimated values (Kiesel, Miller, Jolicœur, & Brisson, 2008; Ulrich & Miller, 2001).

## Results

**Behavior.** The mean response time (RT) for red targets was shorter than for green target trials ( $RT_{\text{R}} = 783 \text{ ms}$ ,  $\sigma = 137.24$ ;  $RT_{\text{G}} = 801 \text{ ms}$ ,  $\sigma = 132.28$ ;  $F(1,19) = 7.00$ ,  $p < .016$ ). Mean accuracy for red targets was not significantly different from accuracy for green targets ( $Acc_{\text{RED}} = 91\%$ ,  $\sigma = .06$ ;  $Acc_{\text{GREEN}} = 92\%$ ,  $\sigma = .06$ ,  $F(1,19) = .45$ ;  $p > .51$ ).

**ERP/ERL.** Using our current paradigm, we expected to see a P<sub>D</sub> at a slightly longer latency compared to the N2pc only in the trials where the distractor was lateral. Hickey et al. (2009) reported a P<sub>D</sub> timing of about 230–280 ms. The lateral distractor trials ERLs, shown in Figure 2, revealed a more complex picture. When a red circle was the lateral distractor, two positive components appeared in the ERL waveforms, one preceding and one following the N2pc, peaking respectively at 142 ms and 296 ms. Based on the results and arguments of Hickey et al. (2009), we associated the second positivity as likely equivalent to the P<sub>D</sub>, whereas the first component would be akin to the Ppc or to the P<sub>D</sub> found by Sawaki and Luck (2010). On the other hand, when the lateral distractor was green there was no significant component visible. The *t* tests against zero for each component are reported in Table 1 for all conditions.

When we examined results for trials with a lateral target (Figure 2), we found the typical N2pc for a lateral red or green target. However, the N2pc was delayed for the lateral green target trials compared to the lateral red target trials (mean onset latency,  $M_{\text{RED}} = 174 \text{ ms}$ ,  $\sigma = 1.26$ ;  $M_{\text{GREEN}} = 210 \text{ ms}$ ,  $\sigma = 1.48$ ;  $F_{\text{CORRECTED}}(1,19) = 64.5$ ;  $p < .0001$ ). A Ppc was present for the red and the green targets. An ANOVA with factors color (red vs. green) and status (target vs. distractor) for each component (N2pc, Ppc, and P<sub>D</sub>) revealed (see Table 2) a color main effect for each component as well as a status main effect for the N2pc. The three components had larger amplitudes for red circles compared to green circles, regardless of their status as target or distractor. The Ppc and the P<sub>D</sub> nearly reached significance for an interaction Color  $\times$  Status, which tended to be supported by the *t* test against zero patterns from Table 1. The Ppc failed to reach significance when the distractor was green, whereas the P<sub>D</sub> only reached significance for a red distractor.



**Figure 2.** Results from Experiment 1. Grand average contralateral minus ipsilateral waveforms, at electrode pair PO7–PO8, for the lateral color singleton, for each color (red vs. green) and status (target vs. distractor). The curves are generally characterized by an early positivity posterior and contralateral (Ppc), followed by an N2pc, and a subsequent P<sub>D</sub>. See text for further details.

The differences between the red and green waveforms encouraged us to look for distractor-related positivity for each color separately. As can be seen in Figure 2, when the target was red we observed the same positivity before and after the N2pc as when the lateral circle was a red distractor. When the target was green, we only saw a Ppc (before the N2pc) and there was no P<sub>D</sub>, while there was neither a Ppc nor a P<sub>D</sub> when the lateral distractor was green.

**Discussion**

The delayed N2pc latency for a green target compared to a red target combined with longer RTs for green targets compared to red

targets suggests a processing difference between red and green that begins at least as early as the N2pc time range. The presence in red distractor trial ERLs of a component such as a Ppc, which is present in red lateral target trials but absent from green lateral distractor trial ERLs, also supports such an interpretation. The red circles show signs of preferential attentional treatment even though their luminance was the same as for the gray and green circles.

These results seem at odds with the suggestion of Hickey et al. (2009) that the P<sub>D</sub> would be related to processes of distractor suppression. The red distractor ERLs show waveforms (Figure 2) similar to the red targets, which should supposedly only show a positive component in the 230 ms to 280 ms time range. On the

**Table 1.** Time Range (ms), Average Amplitude (µV), and T Test Against 0 of Each Component for Each Color and Status Condition of Both Experiments

Experiment	Color	Status	N2pc	Ppc	P <sub>D</sub>
1	Red	Target	205 ms–255 ms <i>M</i> = -3.149 µV; $\sigma$ = 2.2 <i>t</i> (19) = 6.399; <i>p</i> < .00001*	123 ms–153 ms <i>M</i> = .669 µV; $\sigma$ = .99 <i>t</i> (19) = 3.035; <i>p</i> < .007*	295 ms–325 ms <i>M</i> = .731 µV; $\sigma$ = 2.05 <i>t</i> (19) = 1.596; <i>p</i> < .127
		Distractor	199 ms–249 ms <i>M</i> = -.471 µV; $\sigma$ = 1.07 <i>t</i> (19) = 1.967; <i>p</i> < .064	127 ms–157 ms <i>M</i> = .784 µV; $\sigma$ = .62 <i>t</i> (19) = 5.651; <i>p</i> < .00002*	281 ms–311 ms <i>M</i> = 1.089 µV; $\sigma$ = 1.39 <i>t</i> (19) = 3.502; <i>p</i> < .002*
	Green	Target	234 ms–284 ms <i>M</i> = -2.714 µV; $\sigma$ = 1.96 <i>t</i> (19) = 6.186; <i>p</i> < .00001*	148 ms–178 ms <i>M</i> = .428 µV; $\sigma$ = .73 <i>t</i> (19) = 2.627; <i>p</i> < .017*	338 ms–368 ms <i>M</i> = .047 µV; $\sigma$ = 1.72 <i>t</i> (19) = .123; <i>p</i> < .903
		Distractor	199 ms–249 ms <i>M</i> = .124 µV; $\sigma$ = .67 <i>t</i> (19) = .826; <i>p</i> < .419	127 ms–157 ms <i>M</i> = .122 µV; $\sigma$ = .72 <i>t</i> (19) = .761; <i>p</i> < .456	281 ms–311 ms <i>M</i> = -.31 µV; $\sigma$ = .9 <i>t</i> (19) = 1.536; <i>p</i> < .141
2	Red	Target	211 ms–261 ms <i>M</i> = -1.864 µV; $\sigma$ = 1.18 <i>t</i> (20) = 7.256; <i>p</i> < .000001*	115 ms–145 ms <i>M</i> = .686 µV; $\sigma$ = .96 <i>t</i> (20) = 3.274; <i>p</i> < .004*	285 ms–315 ms <i>M</i> = .131 µV; $\sigma$ = 1.58 <i>t</i> (20) = .381; <i>p</i> < .707
		Distractor	209 ms–259 ms <i>M</i> = -.155 µV; $\sigma$ = .92 <i>t</i> (20) = .778; <i>p</i> < .446	123 ms–153 ms <i>M</i> = .617 µV; $\sigma$ = .63 <i>t</i> (20) = 4.513; <i>p</i> < .0003*	269 ms–299 ms <i>M</i> = .799 µV; $\sigma$ = .93 <i>t</i> (20) = 3.952; <i>p</i> < .0008*
	Green	Target	234 ms–284 ms <i>M</i> = -1.915 µV; $\sigma$ = 1.4 <i>t</i> (20) = 6.282; <i>p</i> < .00001*	148 ms–178 ms <i>M</i> = .584 µV; $\sigma$ = .9 <i>t</i> (20) = 2.957; <i>p</i> < .008*	338 ms–368 ms <i>M</i> = .387 µV; $\sigma$ = 2.01 <i>t</i> (20) = .881; <i>p</i> < .389
		Distractor	257 ms–307 ms <i>M</i> = -.121 µV; $\sigma$ = .69 <i>t</i> (20) = .798; <i>p</i> < .434	142 ms–172 ms <i>M</i> = .433 µV; $\sigma$ = .54 <i>t</i> (20) = 3.682; <i>p</i> < .001*	342 ms–372 ms <i>M</i> = .061 µV; $\sigma$ = .92 <i>t</i> (20) = .306; <i>p</i> < .763

\*statistically significant at a *p* < .05 level.

**Table 2.** Average Amplitude ( $\mu\text{V}$ ) and ANOVA F Values of Each Component for Factors Color and Status for Both Experiments

Experiment	Component	Contrast		
		Color	Status	Color $\times$ Status
1	N2pc	$M_R = -1.81 \mu\text{V}; \sigma = 2.18$ $M_G = -1.3 \mu\text{V}; \sigma = 2.04$ $F(1,19) = 4.91$ $p < .039^*$	$M_T = -2.93 \mu\text{V}; \sigma = 2.07$ $M_D = -.17 \mu\text{V}; \sigma = .93$ $F(1,19) = 49.18$ $p < .000001^*$	$F(1,19) = .33$ $p < .57$
	Ppc	$M_R = .73 \mu\text{V}; \sigma = .82$ $M_G = .28 \mu\text{V}; \sigma = .73$ $F(1,19) = 11.77$ $p < .003^*$	$F(1,19) = .31$ $p < .585$	$F(1,19) = 3.4$ $p < .081$
	P <sub>D</sub>	$M_R = .91 \mu\text{V}; \sigma = 1.74$ $M_G = -.13 \mu\text{V}; \sigma = 1.37$ $F(1,19) = 11.68$ $p < .003^*$	$F(1,19) = .00$ $p < .999$	$F(1,19) = 3.22$ $p < .089$
2	N2pc	$F(1,20) = .01$ $p < .943$	$M_T = -1.89 \mu\text{V}; \sigma = 1.28$ $M_D = -.14 \mu\text{V}; \sigma = .8$ $F(1,20) = 32.88$ $p < .00001^*$	$F(1,20) = .07$ $p < .801$
	Ppc	$F(1,20) = 1.88$ $p < .186$	$F(1,20) = .34$ $p < .566$	$F(1,20) = .06$ $p < .804$
	P <sub>D</sub>	$F(1,20) = .79$ $p < .383$	$F(1,20) = .27$ $p < .606$	$M_{TR} = 1.89 \mu\text{V}; \sigma = 1.28$ $M_{DR} = .13 \mu\text{V}; \sigma = 1.58$ $M_{TG} = .06 \mu\text{V}; \sigma = .92$ $M_{DG} = .8 \mu\text{V}; \sigma = .93$ $F(1,20) = 4.43$ $p < .048^*$

\*statistically significant at a  $p < .05$  level.

other hand, green distractor ERLs do not show (Figure 2) any indication of attentional treatment of the lateral item. In addition, the green distractor circle failed to produce any actual status effect between target and distractor for the Ppc as well as the P<sub>D</sub>. We surmise that the difference in positivity following the N2pc as a function of the color of the lateral stimulus reflects a substantial processing imbalance between these particular colors. We note that this difference was not controlled in the Hickey et al. (2009) experiment because their lateral item for critical conditions was always red.

Although the post-N2pc contralateral positivity was not strongly modulated by the target versus distractor distinction, N2pc was very strongly modulated. A large N2pc was observed only when the lateral item was a target, whether this item was red or green.

### Experiment 2

The results of Experiment 1 show that the N2pc should not always be interpreted as the sum of a negativity contralateral to the target (reflecting target selection) and a positivity contralateral to the distractor (reflecting distractor suppression). The marginally significant N2pc for the red distractor trials, combined with its absence in green distractor trials, may indicate that a processing difference across colors led to a partial loss of control during attentional deployment. The simplest explanation would be that during a subset of trials participants deployed their attention to the red distractor first instead of the green target. An alternate explanation would be that the distractor processing during the N2pc time range is proportional to an attentional priority difference between the distractor and the target (here as a function of color).

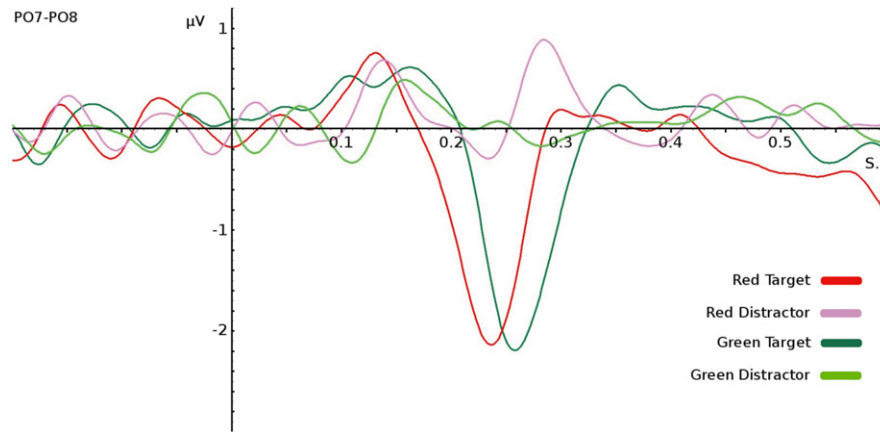
However, we may wonder if the absence of specific distractor-related activity may have resulted from the random selection of

target color (and hence of the distractor color) on each trial. The frequently changing color of the distractor may have prevented the formation of a more stable endogenous bias against a specific distractor color. Woodman, Luck, and Schnall (2007) found, for example, that there was more dual-task interference on visual search by a concurrent requirement to hold information in visual short-term memory when a target defined by shape changed from trial to trial than when the target shape was kept constant during trial blocks. This suggests that holding the selection criteria for the target constant may facilitate the use of a processing strategy that makes visual search less subject to interference from concurrent distractors (perhaps because of a processing of distractor inhibition that is sensitive to concurrent load). In Experiment 2, we tested this possibility by holding the target and distractor color constant throughout each block of trials. We hypothesized that blocking the trials by target/distractor color would enable a stronger top-down control over distractor inhibition, as well as over target selection. Such a greater top-down influence could overcome (in part or in whole) the apparent color imbalance between the green and the red stimuli that was evident in Experiment 1.

### Method

**Participants.** Participants completed the experiment voluntarily and received monetary compensation. They had normal or corrected-to-normal vision, were neurologically normal, and were not taking neurologically active medication. From the 27 participants who completed Experiment 2, 21 were kept for analysis (10 women) with a mean age of 22.2 (19 to 28 years old). The excluded participants were rejected due to excessive numbers of ocular artifacts (blinks and ocular movements toward the lateral singleton). All participants signed an informed consent in accordance with the





**Figure 3.** Results from Experiment 2. Grand average contralateral minus ipsilateral waveforms, at electrode pair PO7–PO8, for the lateral color singleton, for each color (red vs. green) and status (target vs. distractor). The latency difference between the red and green N2pc is still present while blocking target color. The curves are generally characterized by an early positivity posterior and contralateral (Ppc), followed by an N2pc, and a subsequent P<sub>D</sub>. See text for further details.

Université de Montréal Faculty of Arts and Science Ethics Committee guidelines.

**Stimuli, design, and procedure.** Stimuli and task were the same as in Experiment 1, except that instead of specifying the target color at random trial by trial, we alternated the target color (and hence the distractor color) block by block, balancing the order of presentation across participants. As in Experiment 1, there were 8 blocks of 128 trials.

## Results

**Behavior.** As in Experiment 1, the mean RT was shorter for red targets than for green targets ( $RT_{RED} = 739$  ms,  $\sigma = 85.2$ ;  $RT_{GREEN} = 759$  ms,  $\sigma = 83.08$ ;  $F(1,20) = 8.73$ ;  $p < .008$ ). The mean accuracy (percent) did not differ across target color ( $Acc_{RED} = 95.8\%$ ,  $\sigma = .02$ ;  $Acc_{GREEN} = 95.4\%$ ,  $\sigma = .03$ ;  $F(1,20) = 1.31$ ;  $p > .26$ ).

**ERP/ERL.** As reported in Table 1, the results revealed essentially the same general ERL components in Experiment 2 as in Experiment 1. The most important findings, based on the ERLs for lateral distractors and targets, for each color are shown in Figure 3. When the lateral distractor was red, we observed a Ppc and a P<sub>D</sub>, but when the lateral distractor was green, we found only a Ppc, which although visible in the waveform in Experiment 1 did not reach statistical significance in that experiment. When the lateral target was red or green, we observed a Ppc followed by an N2pc. The N2pc was delayed for the lateral green targets compared to the lateral red targets ( $M_{RED} = 203$  ms,  $\sigma = 1.55$ ;  $M_{GREEN} = 229$  ms,  $\sigma = 1.03$ ;  $F(1,20) = 24.9$ ;  $p < .0001$ ). An ANOVA with factors color (red vs. green) and status (target vs. distractor) comparing each component amplitude (N2pc, Ppc, and P<sub>D</sub>) revealed (see Table 2) an expected N2pc status (target vs. distractor) main effect and a Color  $\times$  Status interaction for the P<sub>D</sub>. The P<sub>D</sub> was significantly larger, and significantly different from zero, for a lateral red distractor than for the other conditions. A color amplitude effect was not found for the Ppc or the N2pc.

In order to compare results across experiments, we performed additional analyses by including experiment as a between-subjects

factor in ANOVAs that were otherwise like those used for each experiment. The most important results are summarized in Table 3. We found an interaction between experiment and target-distractor status in which only the lateral targets elicit an N2pc, and the amplitude was larger for mixed trials (Experiment 1) than for blocked trials (Experiment 2) for the N2pc component only. This is a very interesting result because it demonstrates a modulation of the N2pc despite the use of identical stimuli (target, distractor, and fillers), based on whether the target-distractor relationship changed frequently or infrequently. Importantly, this modulation was substantial for both red and green lateral targets and suggests that the N2pc might reflect a greater effort at early stages of processing in order to compensate for a less well-established top-down selection filter. There was also an interaction between color and experiment for the N2pc reflecting a change in the relative amplitude of the N2pc for red and green targets across the experiments. Our interpretation of this result is somewhat speculative, but consistent with the results of Woodman et al. (2007). The changing color assignment from trial to trial in Experiment 1 may have made it more difficult to maintain an effective selection filter for green targets, allowing more bottom-up color differences to influence the results. This would give a greater relative advantage to red in Experiment 1 than in Experiment 2. More work will be needed to verify this speculative hypothesis. We also found a near significant interaction of experiment and color for the Ppc and the P<sub>D</sub>, raising some possibility of a real difference for these components between the two experiments. Averaging across experiments, we found a color main effect, with larger Ppc and P<sub>D</sub> amplitudes for red than for green. The P<sub>D</sub> color main effect was overshadowed by an interaction of status and color reflecting a larger P<sub>D</sub> for lateral red distractors followed by a lateral red target, which is not significantly different from 0,  $t(40) = 1.49$ ;  $p > .14$ , supporting the proposal that the amplitude, if not the presence, of the P<sub>D</sub> was driven by the fact that the lateral item was red.

## Discussion

As in Experiment 1, the N2pc in Experiment 2 was earlier for red targets than for green targets. However, unlike what we found in Experiment 1, there was no amplitude difference across red and

**Table 3.** Average Amplitude ( $\mu\text{V}$ ) and ANOVA F Values of Each Component for Factors Experiment, Color, and Status

Contrast	N2pc	Ppc	P <sub>D</sub>
Experiment	$F(1,39) = 3.18$ $p < .082$	$F(1,39) = .24$ $p < .625$	$F(1, 9) = .02$ $p < .886$
Status	$M_T = -2.4 \mu\text{V}; \sigma = 1.78$ $M_D = -.16 \mu\text{V}; \sigma = .86$ $F(1,39) = 82.08$ $p < .00000001^*$	$F(1,39) = .65$ $p < .426$	$F(1,39) = .13$ $p < .723$
Color	$F(1,39) = 3.78$ $p < .059$	$M_R = .69 \mu\text{V}; \sigma = .8$ $M_G = .39 \mu\text{V}; \sigma = .74$ $F(1,39) = 12.34$ $p < .001^*$	$M_R = .68 \mu\text{V}; \sigma = 1.55$ $M_G = .05 \mu\text{V}; \sigma = 1.47$ $F(1,39) = 9.67$ $p < .004^*$
Experiment $\times$ Status	$M_{T1} = -2.93 \mu\text{V}; \sigma = 2.07$ $M_{D1} = -.17 \mu\text{V}; \sigma = .93$ $M_{T2} = -1.89 \mu\text{V}; \sigma = 1.28$ $M_{D2} = -.14 \mu\text{V}; \sigma = .8$ $F(1,39) = 4.14$ $p < .049^*$	$F(1,39) = .00$ $p < .956$	$F(1,39) = .12$ $p < .731$
Experiment $\times$ Color	$M_{R1} = -1.81 \mu\text{V}; \sigma = 2.18$ $M_{G1} = -1.3 \mu\text{V}; \sigma = 2.04$ $M_{R2} = -1.01 \mu\text{V}; \sigma = 1.35$ $M_{G2} = -1.02 \mu\text{V}; \sigma = 1.42$ $F(1,39) = 4.23$ $p < .046^*$	$F(1,39) = 3.41$ $p < .072$	$F(1,39) = 3.88$ $p < .056$
Status $\times$ Color	$F(1,39) = .31$ $p < .58$	$F(1,39) = 1.52$ $p < .225$	$M_{TR} = .42 \mu\text{V}; \sigma = 1.82$ $M_{DR} = .94 \mu\text{V}; \sigma = 1.17$ $M_{TG} = .22 \mu\text{V}; \sigma = 1.86$ $M_{DG} = -.12 \mu\text{V}; \sigma = .92$ $F(1,39) = 7.64$ $p < .009^*$
Experiment $\times$ Status $\times$ Color	$F(1,39) = .03$ $p < .865$	$F(1,39) = .71$ $p < .403$	$F(1,39) = .2$ $p < .656$

\*statistically significant at a  $p < .05$  level.

green targets. It is likely that participants were able to prepare better when target and distractor colors were constant for entire blocks of trials. Although blocking target and distractor colors reduced the color-related imbalance on N2pc amplitude, it did not remove the latency advantage for red over green also found in Experiment 1. These results are important because they suggest that, despite the use of equiluminant stimuli, there can be systematic differences in the speed with which attention can be deployed to targets selected on the basis of different colors. The latency difference across red and green targets suggests that red has a higher overall attentional priority than green, at least in the present context.

Not only were target-related processes affected by blocking color, but so were those engaged by the distractors. For example, we observed a Ppc for the lateral green distractors in Experiment 2 that was not evident in Experiment 1 (not blocked). The Ppc might function as an “attend-to-me” signal caused by an imbalance in the physical properties of the display. However, the fact that the Ppc was not observed when the distractor color changed randomly from trial to trial (Experiment 1), but was found when the distractor color was constant during whole trial blocks (Experiment 2) suggests that the Ppc may be partially driven by endogenous factors. Sawaki and Luck (2010) were able to make the Ppc disappear by forcing the attention away from the imbalanced element in the display with a difficult task for stimuli at the fixation. Interestingly, here we had the same task and exactly the same physical display across different experiments. The only difference across experiments was whether the role of particular colors varied frequently (across trials) or infrequently (across blocks). If the Ppc reflected only purely exogenous stimulus factors, we should have observed equivalent Ppc

components in the two experiments for both colors. The Ppc was, in fact, quite similar across experiments for red distractors, perhaps because processing for red was more strongly influenced by bottom-up factors. The contextual change induced by mixing versus blocking target and distractor color status had a stronger effect for processing green stimuli, perhaps because green was inherently less salient based on bottom-up signals. The weaker bottom-up influence may have allowed top-down influences to be more easily observed. The blocking of distractor color may have given the lateral green distractor a special status that increased the attentional priority for green, resulting in a significant Ppc in the blocked trials of Experiment 2, perhaps using the same mechanisms as in the paradigm of Woodman et al. (2007). Experiment 2 still showed significant color imbalances that make it difficult to isolate a distractor-specific ERL. The pattern of activation for the lateral red and green distractors both show a Ppc (Figure 3), but only red distractors have a P<sub>D</sub>. The presence of the P<sub>D</sub> for red distractors is tantalizing as potential evidence for a mechanism of distractor suppression given the apparent absence of the component for red targets. One possibility is that the N2pc, which is a strong contralateral negativity, overrides the positivity that might have been visible in the absence of target-specific processing leading to the N2pc on lateral red target trials. Perhaps the most important finding here, therefore, was the complete absence of a P<sub>D</sub> for green distractors, despite blocking distractor color, and clear evidence for a Ppc and N2pc for green targets and a Ppc for green distractors. In short, the pattern of results provides, at best, equivocal evidence for a process of distractor suppression expressed in a contralateral P<sub>D</sub>. We note that the Hickey et al. (2009) experiments all had a red lateral distractor (with subjective brightness matched to the

background) and trials were blocked. This is not to say that the Hickey et al. (2009) results did not reflect distractor suppression. It is entirely possible that the significantly different experimental conditions in their experiments made it possible to observe such a mechanism. Three things are clear from our results. Firstly, lateral distractors do not invariably produce a clear  $P_D$  component. Secondly, the specific colors used in search experiments can have significant influences on patterns of event-related potentials, including lateralized potentials important in the study of visual-spatial attention. And thirdly, the necessary and sufficient conditions needed to observe distractor suppression expressed in a  $P_D$  component are not known at this time. More research is needed to delimit the boundary conditions for this potentially very interesting component.

### General Discussion

The N2pc latency difference in both experiments and the amplitude effect of color in Experiment 1 for the Ppc, N2pc, and  $P_D$  indicate a clear processing imbalance across red and green, despite equi-luminance, which is usually not considered explicitly in most attention experiments. The calculation of the N2pc combines effects from lateral targets and distractors and typically averages over color effects when stimuli are carefully counterbalanced across all conditions. However, this approach may hide interesting systematic differences across stimuli. Such effects were revealed in the present investigation. In both experiments, the red-green color difference dominated the differences between target and distractor for the Ppc and the  $P_D$ , and had a very noticeable latency effect for the N2pc. The blocking of the target color seemed to be sufficient to reduce the amplitude effect of color on the Ppc and N2pc components, but the latency effect remained for the N2pc. This reduction of the color imbalance is possibly explained by the adoption of top-down selection and rejection filters, based on the stable relationship between color and target versus distractor status, when trials are blocked (Woodman et al., 2007). This may have enabled participants to be less strongly influenced by purely bottom-up factors. The Ppc and the  $P_D$  appear to be more strongly related to exogenous, physical properties of the items than to endogenous status imposed by the task. Given the frequent use of red and green as colors in attention experiments, the present results suggest that experimenters should be cautious in how experiments are designed and how results are interpreted. For example, in the work of Hickey et al. (2009), one might wonder to what extent the observed contralateral positivity associated to distractors was due to the consistent use of a red lateral stimulus as distractor, as opposed to a process of distractor suppression. It is possible that the use of a color stimulus matched in brightness with the background, and not balanced by a corresponding stimulus in the opposite hemifield as

in the Hickey et al. (2009) paradigm, would reveal a contralateral positivity to green distractors. Such an experiment would be a useful extension and confirmation of the Hickey et al. (2009) interpretation of the  $P_D$ .

In the present preparation, we did not observe a contralateral positivity, in either experiment, when the lateral distractor was green (and the midline target was red). Hickey et al. (2009) proposed that the  $P_D$  may indicate an inhibition process observable when a distractor is presented laterally, even if the distractor is not overly strong (red line with a similar brightness as the background). It is possible that a green target was such a weak distractor, in the presence of a red target, that a specific active process of distractor suppression was not engaged. However, we remain cautious regarding the existence and meaning of the  $P_D$ . The present results suggest that to observe the  $P_D$  component requires specific conditions, and those conditions were not met by our experiment. A useful test of the functional interpretation of the contralateral positivity ( $P_D$ ) often, but not always, found after the N2pc, would be to repeat experiments such as the present Experiment 2, but with colors chosen to be more equally prioritized, from the point of view of attentional mechanisms. Equal attentional priority could be operationalized as an N2pc of equal amplitude and latency or the absence of a Ppc before the N2pc for lateral targets in those colors.

The present results provide interesting evidence suggesting that the Ppc, the positivity posterior and contralateral observed prior to the N2pc, is not only a reflection of sensory differences across the stimuli. Had this been the case, the Ppc for green lateral distractors should have been the same in the two experiments. Blocking or mixing the role of green as a target or distractor color modulated the amplitude of the Ppc, suggesting therefore that the Ppc is sensitive to experimental context, and thus not simply a reflection of bottom-up sensory differences.

Finally, the results suggest that red stimuli may enjoy a special status in the context of visual search designs like the ones employed in the present work, and in many other similar experiments in the literature (e.g., Hickey et al., 2009; Hillimire, Mounts, Parks, & Corballis, 2009; Mazza, Turatto, & Caramazza, 2009). This possible special status of red occurs despite balancing stimuli for luminance and suggests that further work on the color differences found here would be clearly warranted given the relative impact of this factor. Of course, the present results are quite limited because they examined only a particular red and green color, and as such they invite a broader investigation involving more colors. Our goal was not to offer a definitive solution to the issue, but rather sound an alarm. At the very least, the present work should serve as a *red alert* to all researchers, but particularly to researchers using sensitive electrophysiological methods, to pay close attention to the specific colors used in studies designed to elicit visual event-related responses, and to how they impact the results.

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