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## Inhibition drives early feature-based attention

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### Abstract

Attention can modulate processing of visual input according to task-relevant features, even as early as ~100 ms after stimulus presentation. In the present study, ERP and behavioral data reveal that inhibition of distractor features, rather than activation of target features, is the primary driver of early feature-based selection in human observers. This discovery of inhibition consistent with task goals during early visual processing suggests that inhibition plays a much larger role at an earlier stage of target selection than previously recognized, and highlights the importance of understanding the role of inhibition (in addition to activation) in attention.

### Keywords

visual attention; event-related potentials; feature-based attention; inhibition; event-related potentials

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Because the visual system is limited in its capacity for higher-order processing, engaging in appropriate behavioral responses to external stimuli depends critically on the efficient selection of goal-relevant visual input. This selection process can occur on the basis of several stimulus properties including location (e.g. Posner, 1980) and color (e.g. Green & Anderson, 1956). A recent study (Zhang & Luck, 2009) using event-related potential recordings (ERPs) demonstrated that early processing of task-relevant features throughout the entire visual field can be influenced by current behavioral goals even as early as ~100 ms following stimulus presentation, independent of stimulus location. It is unknown, however, whether this early, global feature-based selectivity operates by *activating* task-relevant features, and/or by *inhibiting* competing distractor features.

Feature-based attention is typically described in terms of activation of task-relevant features (e.g., Wolfe, 1994), often through an increase in the gain of neurons preferentially tuned to target features (e.g., Saenz, Buracas, & Boynton, 2002). More recently, inhibition has been shown also to play a role in feature-based attention; features can be de-prioritized depending on factors such as recent experience (Braithwaite & Humphreys, 2003; Lleras, Kawahara, Wan, & Ariga, 2008). However, while electrophysiological data indicate *location*-based inhibition can occur during early stages of visual processing (~100 ms post-stimulus; Luck et al., 1994; Luck & Hillyard, 1995), evidence of *feature*-based inhibition has typically been found only at later stages of processing (starting ~200–300 ms post-stimulus; Andersen & Müller, 2010; Shin, Wan, Fabiani, Gratton, & Lleras, 2008). To our knowledge, there is no evidence that feature-based inhibition can influence earlier stages of visual processing.

We adapted Zhang and Luck's (2009) paradigm to include a baseline task-neutral color in order to determine whether feature-based inhibition influences selection early in visual processing. Observers viewed a continuous stream of two spatially interleaved sets of dots in one visual hemifield while maintaining central fixation (Figure 2a). Observers were instructed to indicate whenever the target-colored dots were simultaneously dimmed for 500 ms, but to ignore occasions when it was the distractor-colored dots that dimmed simultaneously. During each trial, task-irrelevant homogeneously colored sets of dots (probes) were occasionally presented in the opposite hemifield. Within each trial, each set of probe dots was randomly selected to be composed of dots matching either the target color from the task-relevant side, the distractor color from the task-relevant side, or a neutral color that never appeared on the task-relevant side.

We examined changes in the amplitude of the P1 response to these probe stimuli to examine the effects of feature-based attention on early visual processing. The P1 is an ERP component that reflects an early sweep of visual processing (~100 ms after stimulus presentation) whose amplitude can be affected by changes in neuronal activity in extrastriate cortex (e.g., Mangun, Buonocore, Girelli, & Jha, 1998; Woldorff, et al., 1997) that may reflect top-down attentional control settings (e.g., Hillyard & Münte, 1984). The P1 is typically interpreted to reflect a feedforward wave of sensory processing (e.g., Hillyard, Vogel, & Luck, 1998, Luck & Kappenman, 2012, Zhang & Luck, 2009; but see also Foxe & Simpson, 2002 for an alternative interpretation)

## Experiment 1

### Materials and Methods

Twenty-one Johns Hopkins community members (9 male, mean age = 25.7 years) participated in sessions lasting 1.5–2 hours. Stimulus presentation and data analysis were performed using MATLAB (Mathworks) and PsychToolbox software (Brainard, 1997). EEG data were recorded at 47 sites covering the whole scalp with approximately uniform density using an elastic electrode cap (Waveguard cap with 128-channel Duke [equidistant electrode placement] layout, made by Advanced Neuro Technology [ANT], the Netherlands; Figure 1), referenced to the average of all channels during recording. Electrode impedance was kept below 5 k $\Omega$ . All EEG channels were recorded continuously in DC mode at a sampling rate of 512 Hz from a 128-channel, high-impedance ANT Waveguard amplifier with active cable-shielding technology and an anti-aliasing low-pass filter with a 138Hz cutoff.

**Stimuli**—Throughout every trial, sets of small dots (each dot subtending 0.14° of visual angle) were presented in both hemifields on a black background. The dots in each hemifield were randomly placed within an imaginary circle with a radius subtending 3.34° of visual angle, centered 6.37° (horizontal) and 1.71° (vertical) of visual angle from fixation (Figure 2a).

In the task-relevant hemifield, 100 spatially intermingled target-colored and distractor-colored dots (50 each) were presented. Target and distractor colors were randomly selected without replacement for each participant to be red, green, or blue throughout the entire experiment, counterbalanced across participants. Each color appeared at a luminance of 8.1 cd/m<sup>2</sup>. On the task-relevant side, the luminance of all of the dots of one color was occasionally reduced to 3.2 cd/m<sup>2</sup>. Throughout each trial, in the opposite (or task-irrelevant) hemifield, probes composed of 50 homogeneously colored dots, randomly selected to be entirely red, green, or blue for each presentation, were presented at varied intervals at a luminance of 8.1 cd/m<sup>2</sup>.

**Design and Procedure**—Each trial began with a central arrow, randomly pointed either left or right, indicating the hemifield in which task-relevant dots would appear on the upcoming trial. After one second, a fixation cross replaced the arrow. Participants were instructed to maintain fixation throughout each trial. After a 0.5 second delay, target and distractor dots appeared in the task-relevant hemifield. Every 100 ms, 50% of all dots were randomly relocated within the imaginary circle in the task-relevant hemifield, giving the dots a scintillating, motion-like appearance (dot motion parameters were based on Zhang & Luck, 2009). During each 15-second trial, the target dots occasionally underwent a brief (500 ms) luminance decrement before returning to their original luminance. Luminance decrements also occurred among the distractor dots, but the two events (target decrements and distractor decrements) were independently timed. These “luminance events” occurred between 2 and 5 times for each color during each trial. Participants were instructed to press the space bar every time a luminance event occurred among the target dots, but not to respond to luminance events among the distractor dots. In the opposite (task-irrelevant) hemifield, probes were presented at inter-stimulus intervals that varied randomly from 217 to 700 ms. Each probe presentation lasted 100 ms and required no overt response.

Following each trial, a blank black screen was presented for 800–1200 ms. Participants completed a minimum of 6 blocks of trials. Each block consisted of 16 trials, with a brief rest between trials 8 and 9. Experimenters provided feedback between blocks on task performance and eye and body movements in order to acquire the cleanest possible signal from EEG recordings.

**Data Analysis**—Three participants were removed either for poor behavioral performance or excessive EEG noise (assessed offline by an experienced electrophysiologist, JBE, who was blind to the experimental conditions).

EEG epochs were synchronized with the onset of probe dot presentation and analyzed using ANT’s ASA software. Vertical Electro Oculograms (VEOG) were recorded from frontal channels LL1 and RR1 (see Figure 1), whose locations were designed specifically to capture eye blinks. Horizontal Electro Oculograms (HEOG) were recorded from channels LE1 and RE1, whose locations were designed specifically to capture horizontal eye movements. Eye blink correction was performed using a principal components analysis method that models the brain signal and artifact subspaces (Ille, Berg, & Scherg, 2002). After eye blink correction, EEG was visually inspected on a trial-by-trial basis to look for any horizontal eye movements. Any trials contaminated with horizontal eye movements were eliminated from averaging. In addition, trials contaminated with excessive muscle artifacts, artifacts due to movements, or trials where amplifier blocking occurred were also eliminated. Although it is possible that a few eye movements to the attended side were undetected, there is no reason to expect that this behavior would differentially affect ERP responses to probes depending on the probe color.

An offline bandpass filter (Butterworth filter, low cut-off frequency 0.2 Hz, high cut-off frequency 35 Hz and linear roll-off 24 dB/oct) was applied to all channels. ERPs were averaged offline from 100 ms before to 600 ms after probe stimulus onset. Data were analyzed from six spatially contiguous electrodes in each hemisphere (LA5, LB4, LC6, LE3, LL10, LL13; RA5, RB4, RC6, RE3, RR10, and RR13; red circled electrodes in Figure 1). These electrodes were selected by experienced electrophysiologists, JBE and BML, on the basis of whether there were discernible P1 patterns present. The electrophysiologists were blind to experimental conditions during this selection process. Finally, grand averaging of ERP waveforms was performed on data obtained from the selected electrodes listed above using EEGLAB/MATLAB (Delorme & Makeig, 2004).

Mean P1 amplitude was calculated for each participant as the mean amplitude from the point in time when the voltage reached 50% of peak amplitude to 50 ms after that point.

## Results

**Behavior**—Task performance was well below ceiling (hit rate = 85.2%, false alarm rate = 8%), suggesting that the task was attention-demanding and likely required the use of limited attentional resources.

The inclusion of a neutral-colored probe was intended to serve as a baseline measure for feature-based attention effects. However, because the neutral color never appeared in the task-relevant hemifield, observers were not exposed to the neutral color as frequently as the other colors. Thus, one might be concerned that neutral-colored probes may have captured spatial attention due to their relative novelty (e.g., Johnston, Hawley, Plewe, Elliott, & DeWitt, 1990). Although attention can increase the magnitude of the P1 response (e.g. Hillyard & Münte, 1984), this has only been demonstrated in situations where observers have a preset attentional bias (i.e. attention is biased to a particular location or feature *prior* to stimulus onset); thus, involuntary capture elicited by stimulus properties should not affect P1 magnitude. Furthermore, there is no evidence, to our knowledge, of novelty affecting any ERP component earlier than the N1 (e.g., Friedman, Cycowicz, & Gatea, 2001; Parmentier, 2008). Therefore there is no reason to believe that the magnitude of the P1 to neutral colored probes would be increased because of its relative novelty.

Nevertheless, in order to assess any possible probe-induced attentional capture, we analyzed luminance detection performance according to which type of probe most recently appeared in the task-irrelevant hemifield before each luminance change. If neutral-colored probes capture spatial attention, we would expect more errors when the most recent probe before a luminance change was neutral-colored than when it was target-colored or distractor-colored. We conducted a 3(probe type) x 6(block) ANOVA on luminance detection error rate and found main effects of probe type,  $F(2,34) = 9.21, p < .01$ , and block,  $F(5,85) = 5.45, p < .001$ , that were mediated by a significant interaction,  $F(10,170) = 3.54, p < .001$  (Fig. 2b). Post-hoc tests revealed that there was a main effect of probe type in blocks 1 and 2 ( $ps < .01$ ), and subsequent Tukey's HSD comparisons showed that the error rate was higher following neutral probes compared to other probes in those first two blocks ( $ps < .05$ ). There was no effect of probe type in the remaining blocks ( $ps > .05$ ). These results indicate that the neutral-colored probe likely captured spatial attention early in the experiment, but by the third experimental block, observers had experienced a sufficient number of neutral probe stimuli to eliminate novelty-based capture.

**EEG**—We conducted a 3(probe type) x 2(hemifield: left vs. right) ANOVA on mean P1 amplitude in response to probes appearing in the contralateral visual hemifield. As a precaution, the first two blocks were not included in this analysis to avoid novelty effects in the baseline measure. To further reduce the possibility that P1 responses to probes were influenced by shifts of spatial attention, any probe for which the observer failed to detect a luminance event in the two seconds before probe onset was excluded from analysis.

There was a main effect of probe type on P1 amplitude,  $F(2,34) = 6.07, p < .01$ . There was no effect of hemifield or interaction between hemifield and probe type ( $F_s > .1$ ). Tukey's HSD post-hoc tests revealed that the mean P1 amplitude in response to target-colored probes was greater than the mean P1 amplitude in response to distractor-colored probes,  $p < .05$  (Figure 3), replicating previous findings of early prioritization of target over distractor features during early visual processing (Zhang & Luck, 2009).

The neutral-colored probes allowed us to determine whether this prioritization reflected activation of target features or inhibition of distractor features. If target activation was the key process, we would expect the mean P1 amplitude in response to *target*-colored probes to be *greater* than the baseline mean P1 amplitude evoked by neutral-colored probes. If distractor inhibition was the key process, we would expect the mean P1 amplitude in response to *distractor*-colored probes to be *smaller* than the baseline (neutral) P1. We found only the latter to be the case; the mean P1 amplitude in response to distractor-colored probes was smaller than the mean P1 amplitude in response to neutral-colored probes,  $p < .01$ , but there was no significant difference between neutral-colored probes and target-colored probes,  $p > .1$  (Figure 3). These data suggest that feature-based attention modulates visual input at an early stage of processing via inhibition of distractor features rather than activation of target features.

## Experiment 2

We drew conclusions in Experiment 1 by comparing the mean P1 amplitude in response to target and distractor-colored probes against a baseline P1 obtained from neutral-colored probes. However, a potential concern in our interpretation is that the neutral color appeared less frequently than the other colors globally. That is, while all three colors appeared with equal probability as probes on the task-irrelevant side of space, the neutral color never appeared on the task-relevant side of space – only the target and distractor colors ever appeared on that side. As a result, it is possible that the P1 responses to the target and distractor-colored probes were attenuated due to sensory adaptation effects (e.g., Luck & Hillyard, 1994), but that no such reduction occurred in response to the less common neutral-colored probe. This would not account for the difference between target and distractor-colored probes. However, it would impact our interpretation of the neutral, baseline condition. Specifically, it could be the case that the P1 amplitude in response to distractor-colored probes was smaller in magnitude than the P1 amplitude in response to the neutral-colored probes not because of attentional inhibition due to task goals, but instead because of adaptation effects that impacted the distractor-colored probe more than the neutral-colored probe.

To rule out the sensory adaptation account, we conducted a control study in which we used the exact same stimuli and procedures as Experiment 1 but in a passive viewing task (i.e., no overt responses were required). If the amplitude of the P1 in response to target-colored and distractor-colored probes was attenuated in Experiment 1 because of sensory adaptation effects, we would expect the P1 response to neutral-colored probes in a passive viewing task to be greater than the P1 amplitude in response to other-colored probes that are rendered in colors that appear on both sides of fixation.

## Methods

All methods were identical to Experiment 1 with the following exceptions. Thirteen Johns Hopkins community members (7 male; mean age = 22.9 years) participated in sessions lasting 1.5–2 hours. One participant was removed for excessive EEG noise due to sleepiness (EEG assessed offline by an experienced electrophysiologist, BLM, who was blind to the experimental conditions). No overt response was required to any event during the course of the experiment; instead, observers were instructed to simply focus on the central fixation cross while stimuli were presented. Electrophysiological data were continuously monitored, and observers were reminded to stay awake and focus on the central fixation if there was any indication that they were falling asleep due to the boredom of the task. All participants completed either 5 or 6 blocks of trials.

Data were analyzed from four spatially contiguous electrodes in each hemisphere (LA5, LC6, LE3, LL13; RA5, RC6, RR10, and RR13; Figure 1). As in Experiment 1, these channels were selected based on whether they showed a clear P1 during condition-blind analysis by JBE and BML. The difference in the selected electrode subsets between the two experiments is likely a result of the differences in task demands; previous studies have shown that the P1 component can be affected by factors such as arousal or attentional demands (e.g., Hopfinger & West, 2006; Vogel & Luck, 2000). Finally, to provide the strictest possible test for any effects of stimulus frequency, all runs from each participant were included in the analysis. By including the early runs, we increase the probability of finding any effects of stimulus frequency on P1, including those that might dissipate over time<sup>1</sup>.

On the side of fixation where probes did not appear, referred to as the “task-relevant” side in Experiment 1, two different groups of colored dots were presented, as in Experiment 1. However, unlike in Experiment 1, there is nothing to distinguish either of these colors as the “target” or “distractor” color. Therefore, for data analysis, we collapsed the data from all probes into two categories: neutral probes, and non-neutral probes. However, we also arbitrarily labeled one color as “target” and the other as “distractor” for each subject, and present probe data separately for those two conditions in Figure 4, to give the reader a sense of the variability in the data. This is particularly important since we hypothesize no difference among the probe conditions.

## Results

We conducted a 2(probe type) x 2(hemifield: left vs. right) ANOVA on mean P1 amplitude in response to probes appearing in the contralateral visual hemifield to determine whether probe type had any effect on P1 amplitude in the absence of a task. If global stimulus frequency modulated the amplitude of the P1 in response to neutral-colored probes in Experiment 1, we would expect a main effect of probe type, with greater P1 amplitude in response to neutral-colored probes than non-neutral (i.e., “target” and “distractor”) colored probes. However, we found no main effect of probe type on mean P1 amplitude,  $F(1,11) < 1$ ,  $p = .61$  (Figure 4). There was a main effect of hemifield,  $F(1,11) = 5.13$ ,  $p < .05$ , with higher mean P1 amplitude in the right brain hemisphere (in response to probes presented to the left visual hemifield) than in the left brain hemisphere (in response to probes presented to the right visual hemifield), but critically, this did not interact with probe type,  $F(1,11) < 1$ .

Proving a negative is difficult; therefore, as additional support to our null results (e.g., de Graaf & Sack, 2011), we also report here the effect size of the probe type factor in Experiment 2 as  $\eta_p^2 = .025$ . In contrast, the effect size of the probe type factor in Experiment 1 was  $\eta_p^2 = .263$ , meaning that the effect of probe type in Experiment 2 was less than 10% the size of the effect in Experiment 1.

These data, along with Figure 4, demonstrate that the adaptation account of Experiment 1 is extremely unlikely. The difference in global frequency among the colors presented in the current paradigm appears to have little effect on P1 amplitude. This provides further support for the distractor inhibition account of feature-based attention effects found in Experiment 1.

## Experiment 3

In Experiment 3, we sought converging behavioral evidence that the luminance detection task induced an inhibitory (rather than excitatory) feature-based attentional set. Each participant performed a shortened version of the task from Experiment 1 (Task 1), and then

<sup>1</sup>Statistical outcomes did not differ if runs one and two were removed from the analysis, as in Experiment 1.



immediately performed a visual search task (Task 2) in which the same colors were used. Previous studies have shown that attentional control settings are often robust, continuing to bias selection even when task goals change (e.g. Leber, Kawahara, & Gabari, 2009). Therefore, this design allowed us to measure the effect of attentional control settings induced by the luminance detection task on later behavior to determine whether they reflect target activation, distractor inhibition, or both.

## Materials and Methods

Eighteen Johns Hopkins community members (5 male; mean age = 23.8 years) participated in sessions lasting approximately 1 hour. Stimulus presentation and data analysis were performed using MATLAB (Mathworks) and PsychToolbox software (Brainard, 1997).

## Stimuli

Stimuli for Task 1 were identical to Experiment 1. For Task 2, 24 letters (each approximately  $0.57^\circ$  of visual angle) appeared on each trial. The target letter was randomly selected for each trial to be “N” or “Z,” and the remaining letters were an approximately equal distribution of “H,” “I,” “V,” and “X.” The location of each letter was randomly selected from an array of 396 possible locations subtending approximately  $19.23^\circ$  of visual angle. The 24 letters appeared in an equal distribution of four different colors – red, green, and blue, all equivalent to the high luminance versions ( $8.1 \text{ cd/m}^2$ ) from Task 1, and an equiluminant yellow. The target color was randomly assigned for each trial.

## Design and Procedure

Participants performed four blocks of Task 1, lasting approximately 30 minutes. As in Experiment 1, red, green, and blue were counterbalanced across subjects in their assignment as the target, distractor, and neutral colors. Following completion of Task 1, participants performed three blocks of Task 2. Each block consisted of 100 trials with a brief rest halfway through each block. On each trial, the search display appeared after a one second fixation interval. Participants indicated which target letter was present with a keypress.

## Results

We conducted a  $3 \times 4$  ANOVA with factors of block (1–3) and target color for Task 2. All response times 2.5 standard deviations above or below the mean in each condition for each participant were removed from analyses (2.9% of all trials). Target color was defined according to what role each color was assigned in Task 1 for each participant: Task 1 target color, Task 1 distractor color, Task 1 neutral color, or novel color.

There was a main effect of block,  $F(2,34) = 5.31, p < .05$ , explained by a linear trend with faster response times during later blocks,  $F(3,51) = 14.57, p < .01$ . There was no main effect of target color,  $F(3,51) = 1.46, p > .1$ .

There was an interaction between block and target color, seen in Figure 5,  $F(6,102) = 3.91, p < .01$ . We conducted separate one-way ANOVAs for each block to assess the effect of target color; only block 1 was significant,  $F(3,51) = 6.7, p < .01$ . This suggests that feature-based attentional control settings induced by Task 1 affected behavior during block 1 of Task 2, but did not affect performance on blocks 2 and 3.

For block 1, we conducted pairwise comparisons for each color combination. Slower response times to targets appearing in the Task 1 distractor color relative to the neutral and novel colors would suggest that Task 1 induced an inhibitory feature-based attention set. Faster response times to targets appearing in the Task 1 target color relative to the novel and neutral colors would indicate a target activation-based attention set. Response times were

slower when the target appeared in the Task 1 distractor color relative to all other colors ( $ps < .05$ ). No other comparisons were significant ( $ps > .1$ ). These data provide converging evidence with Experiment 1, suggesting that the feature-based attentional set induced by Task 1 is defined by inhibition of the distractor color rather than activation of the target color.

## General Discussion

We found the neural response evoked by distractor-colored probes was reduced relative to the response evoked by neutral-colored probes early in visual processing. Furthermore, we found no evidence for an increased neural response to target-colored probes relative to neutral-colored probes. Together, these data suggest that feature-based attention can modulate incoming sensory input at an early stage of processing via inhibition of distractor features. Converging behavioral evidence indicated that attentional control settings based on distractor inhibition were sufficiently robust to carry over to a novel task.

Previous neurophysiological studies in monkeys have shown that neuronal responses are suppressed when a neuron's non-preferred feature is attended (Khayat, Neibergall, & Martinez-Trujillo, 2010; Martinez-Trujillo & Treue, 2004), and other studies have found electrophysiological evidence for inhibitory mechanisms in feature-based attention in humans (Andersen & Müller, 2010; Bridwell & Srinivasan, 2012; Shin, Wan, Fabiani, Gratton, & Lleras, 2008; Snyder & Foxe, 2010). However, in the present study, we show evidence for inhibition of a *specific* competing distractor feature, rather than inhibition of responses to all non-target features, occurring during *early* visual processing in human observers. Furthermore, the data appear to reflect a purely inhibitory mechanism; we find no evidence for target activation during the P1 timeframe in the present task.

The absence of selective activation of the target feature was surprising. Previous research has demonstrated that feature-based attentional effects (albeit weak ones) can occur in the absence of direct competition (Saenz, Buracas, and Boynton, 2003); therefore it remains unlikely that activation plays no role in feature-based attention. However, it appears from the present data that when there is strong competition from distractor stimuli, attention mediates early visual processing primarily through inhibition (and not activation).

Additional research is necessary to understand how higher-level cognitive processes influence early feature-based effects. For example, we (Moher & Egeth, 2012) have found that observers are unable to *explicitly* ignore non-target features that change on a trial-by-trial basis unless they first select those items (but see also Woodman & Luck, 2007). Furthermore, several EEG studies where target and distractor feature values shifted from trial-to-trial (Andersen & Müller, 2010; Shin et al., 2008) failed to find evidence for feature-based inhibition during early visual processing. To reconcile these previous results with the current findings (in which target and distractor feature values were held constant for each individual participant) we propose that there may be two mechanisms by which feature-based attention biases visual input.

The first is a rapidly initiated attentional set characterized by activation of target features, which can be adjusted to accommodate frequently changing goal states. For example, if a new target feature is cued before a trial, an observer can establish an attentional set to activate visual input matching that feature. This is consistent with ERP data demonstrating activation of target features when the target feature changed frequently (e.g. Andersen & Müller, 2010; Andersen, Müller, & Hillyard, 2009). This type of quickly accessible feature-based set would be especially useful in dynamic visual environments where task goals and task-relevant features change frequently. However, in more stable environments where task-



relevant features remain consistent, a different type of feature-based attentional set may be implemented over time. This set effectively modulates visual input at a very early stage via inhibition of distractor features rather than activation of target features. This would be consistent with the present study, in which the target and distractor features were unchanged throughout the experiment. The shift from an excitatory to an inhibitory mode of operation may reflect a gradual, implicit development of an attentional template in long-term memory as target and distractor feature values are learned over time (e.g., Carlisle, Arita, Pardo, & Woodman, 2011). Why might such a template develop? One speculative possibility is that the inhibitory set is metabolically more efficient (e.g., Buzsáki, Kaila, & Raichle, 2007).

Previous research has demonstrated that a to-be-ignored location (e.g., Serences, Yantis, Culbertson, & Awh, 2004) or a single (and thus spatially localized) popout distractor (e.g., Ipata, Gee, Gottlieb, Bisley, & Goldberg, 2006) can be inhibited during early visual processing. The present study suggests that distractor features *themselves* can also be inhibited during an early stage based on current task goals. These findings highlight a critical role for inhibition that merits consideration in future studies and models of attention.

## Acknowledgments

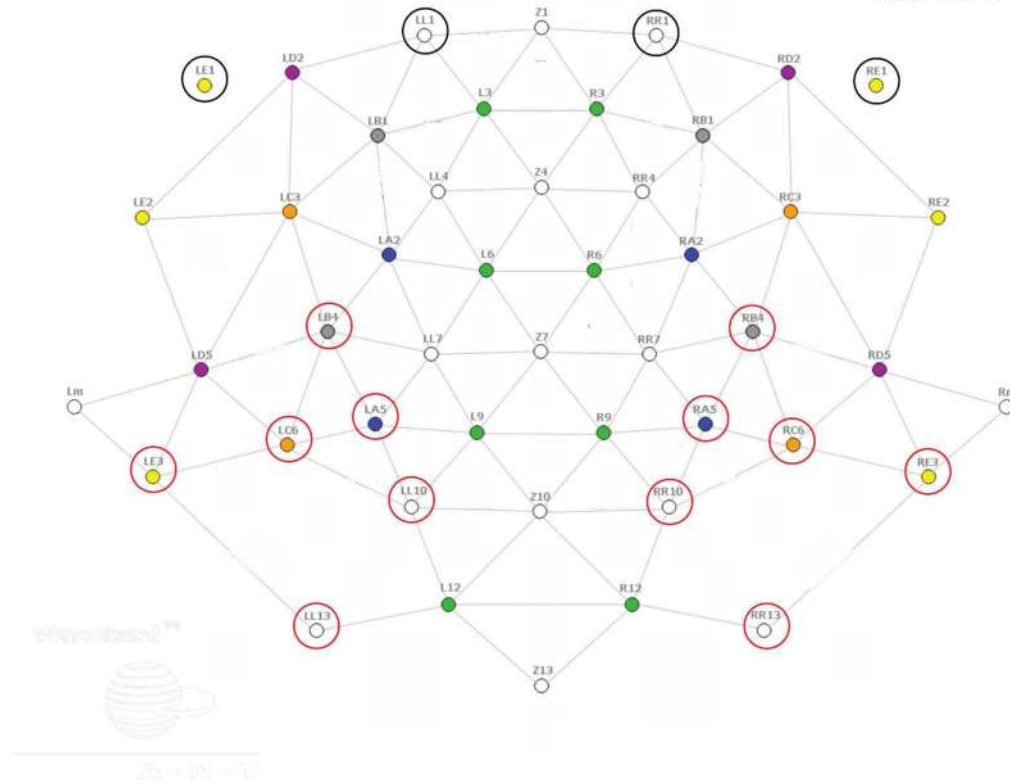
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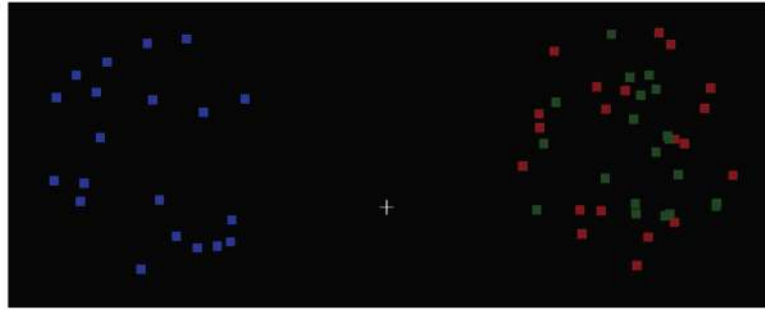
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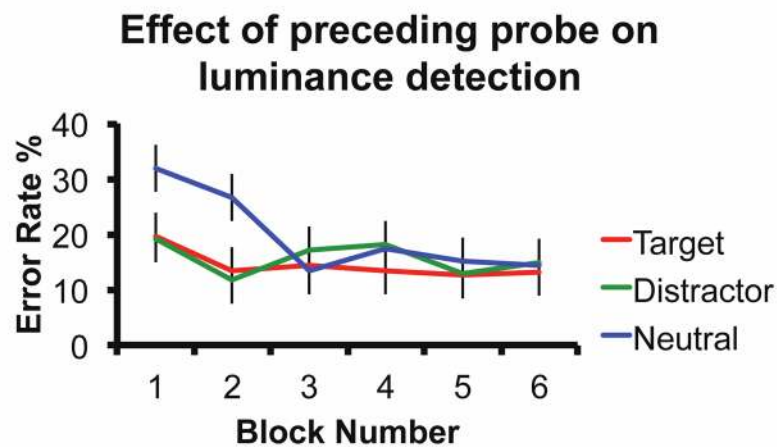


**Figure 1.** The electrode layout used in the present experiment (a subset of 47 of the 128 channels shown were recorded). A spatially contiguous array of electrodes from the recorded channels was collapsed and examined for P1 analysis (highlighted in red circles) including LA5, LB4, LC6, LE3, LL10, LL13, RA5, RB4, RC6, RE3, RR10, and RR13. LE1, RE1, LL1, and RR1 (highlighted in black circles) were used to detect eye movements.

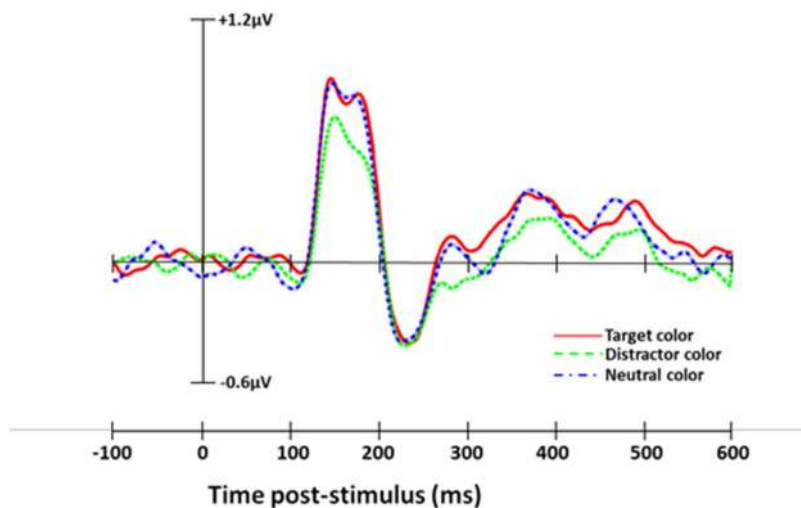
a)



b)

**Figure 2.**

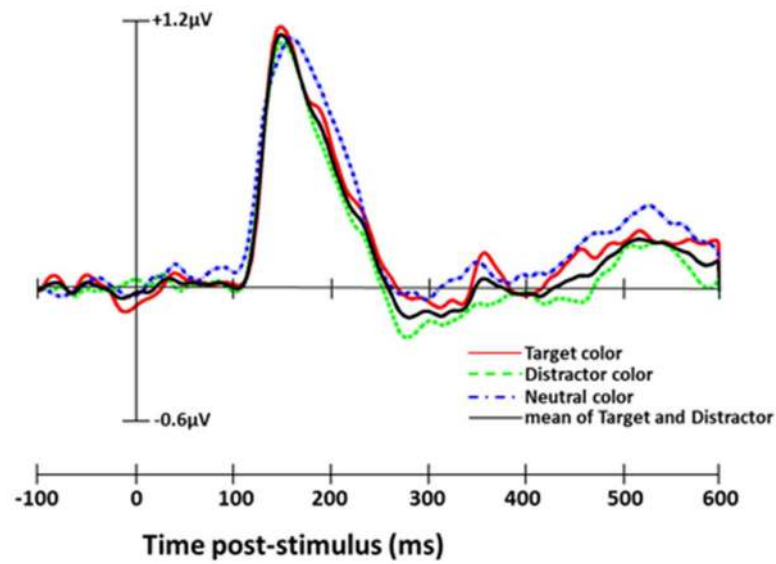
a) A sample frame from within a trial (not to scale). In this example, the observer would be monitoring for luminance changes among the red (target) dots but not among the green (distractor) dots in the right (task-relevant) hemifield. In the left (task-irrelevant) hemifield, probes would occasionally appear in the target color, distractor color, or neutral color (blue in this example, as pictured here). These probes required no overt response, but we examined ERP components elicited by these probes to investigate the influence of feature-based attention on early visual processing. b) Error rate on the luminance detection task as a function of the preceding probe stimulus in the task-irrelevant hemifield. Error rate was higher following neutral-colored probes compared to other probes in the first two blocks, suggesting that the neutral probes may have captured spatial attention, likely due to novelty effects. There was no effect of probe color on the remaining blocks, suggesting that the “novelty” of the neutral color wore off by the third block of trials. Error bars calculated using a within-subjects interaction error term (Loftus & Masson, 1994).



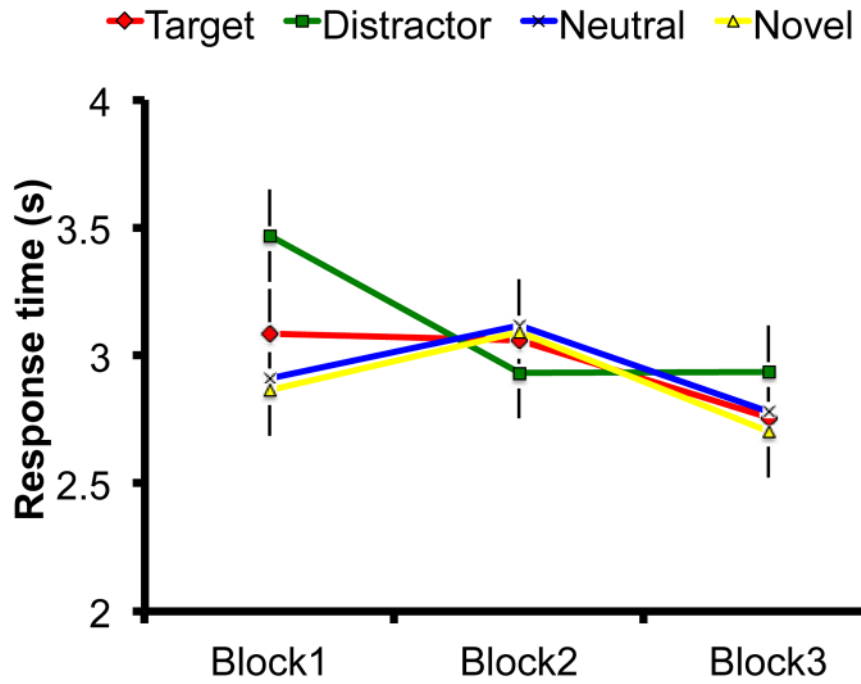
**Figure 3.**

ERP data for probes presented in the task-irrelevant hemifield appearing in the target color (red line), distractor color (green line), and neutral color (blue line) in the contralateral hemifield (right and left hemifield presentations collapsed). Mean P1 amplitude for selected electrodes (circled in red on Figure 1) was significantly greater for target and neutral colors compared to distractor colors, demonstrating feature-based inhibition in early visual processing. There was no significant difference in P1 amplitude between target and neutral colors, suggesting that target activation did not occur during early visual processing.





**Figure 4.** ERP data for probes presented in Experiment 2. Red and green represent the “target” and “distractor” colors respectively; however, since these are arbitrary labels, the black line represents the combination of the two. Blue represents the neutral baseline color that only appeared in the “task-irrelevant” hemifield. We found no difference in mean P1 amplitude among any of the conditions.



**Figure 5.** Data from Task 2 in Experiment 3. Response times in block 1 were slower when the target appeared in the Task 1 distractor color. No other differences were significant. These data suggest that Task 1 induced a feature-based attentional set focused on distractor inhibition rather than target activation. This set initially influenced behavior in a novel task. Error bars calculated using a within-subjects interaction error term (Loftus & Masson, 1994).