

# Attentional Capture by Salient Distractors during Visual Search Is Determined by Temporal Task Demands

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## Abstract

■ The question whether attentional capture by salient but task-irrelevant visual stimuli is triggered in a bottom-up fashion or depends on top-down task settings is still unresolved. Strong support for bottom-up capture was obtained in the additional singleton task, in which search arrays were visible until response onset. Equally strong evidence for top-down control of attentional capture was obtained in spatial cueing experiments in which display durations were very brief. To demonstrate the critical role of temporal task demands on salience-driven attentional capture, we measured ERP indicators of capture by task-irrelevant color singletons in search arrays that could also contain a shape target. In Experiment 1, all displays were visible until response onset. In

Experiment 2, display duration was limited to 200 msec. With long display durations, color singleton distractors elicited an N2pc component that was followed by a late Pd component, suggesting that they triggered attentional capture, which was later replaced by location-specific inhibition. When search arrays were visible for only 200 msec, the distractor-elicited N2pc was eliminated and was replaced by a Pd component in the same time range, indicative of rapid suppression of capture. Results show that attentional capture by salient distractors can be inhibited for short-duration search displays, in which it would interfere with target processing. They demonstrate that salience-driven capture is not a purely bottom-up phenomenon but is subject to top-down control. ■

## INTRODUCTION

A salient visual stimulus such as a unique red item presented among numerous blue items (a feature singleton) often elicits rapid shifts of spatial attention. One of the most enduring controversies in attention research relates to the question whether such shifts can be triggered in a purely bottom-up (stimulus-driven) fashion or whether they are always mediated by top-down (goal-directed) control settings. According to the bottom-up view, the initial allocation of attention is determined solely by physical stimulus properties: Attention is rapidly and automatically attracted by the largest local feature contrast in a visual array, regardless of current top-down task sets (Theeuwes, 2010). The most compelling evidence for bottom-up attentional capture comes from the additional singleton paradigm developed by Theeuwes (1991, 1992). When observers search for a shape singleton target presented among nontarget shapes (e.g., a diamond among circle distractors), RTs are delayed on trials in which a salient but task-irrelevant color singleton is simultaneously present in the visual search array, relative to trials without a color distractor. This distractor interference effect has been attributed to salience-driven bottom-up attentional capture by color singletons that is triggered in spite of the fact that color is completely task irrelevant.

The bottom-up account of attentional capture has not remained unchallenged. In a series of studies by Folk and colleagues (Folk & Remington, 1998; Folk, Remington, & Wright, 1994; Folk, Remington, & Johnston, 1992), spatial cueing procedures were employed to demonstrate that singleton capture is determined by current top-down task sets. On each trial, spatially nonpredictive singleton cues preceded visual search displays, and attentional capture by singleton cues was inferred from the presence of spatial cueing effects (i.e., faster RTs in response to visual search targets at cued relative to uncued locations). Such spatial cueing effects were found only when cues matched the current task set (e.g., for color singleton cues in blocks in which targets were also color singletons) but not for cues with task-irrelevant features. This pattern of results gave rise to the contingent involuntary orienting hypothesis (Folk et al., 1992), which postulates that attentional capture is not an inevitable consequence of bottom-up salience but will only be elicited by salient visual stimuli that match currently task-relevant attributes.

The roles of bottom-up and top-down factors in attentional capture are still debated. In support of the bottom-up view, Theeuwes (2010) argued that the presence of spatial cueing effects for task-set-matching cues and their absence for nonmatching cues, as observed by Folk and colleagues, does not provide unequivocal evidence for task set contingent attentional capture. His claim is that singleton cues will always trigger attention shifts, independently of current task sets, but that attention is then rapidly disengaged from stimuli that have no task-set-relevant

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attributes. Because rapid bottom-up attentional capture is immediately followed by rapid disengagement from non-matching cues before the presentation of subsequent targets, no behavioral spatial cueing effects will be triggered by such cues (see also Theeuwes, Atchley, & Kramer, 2000). In support of the top-down view, Folk and Remington (1998) have argued that the RT costs associated with the presence of a salient but irrelevant distractor in the additional singleton paradigm does not provide incontrovertible evidence for bottom-up capture. They claim that these costs arise as a result of the visual complexity of search arrays that contain two singleton stimuli. This extends the duration of preattentive processing (preattentive filtering costs; see also Kahneman, Treisman, & Burkell, 1983) and delays shifts of attention to target stimuli, resulting in delayed responses on distractor-present trials that are not the result of salience-driven attentional capture by distractors.

It will be obvious that these arguments depend on very specific assumptions about the time course of attentional capture and attentional target selection, which are difficult to test on the basis of behavioral measures alone. For this reason, brain ERP markers of selective attentional processing now play an increasingly important role in current debates about the top-down versus bottom-up control of attentional capture. In several recent studies, the N2pc component has been employed as a temporally precise measure of attentional capture by salient stimuli in visual search arrays (e.g., Eimer, Kiss, Press, & Sauter, 2009; Eimer & Kiss, 2008; Lien, Ruthruff, Goodin, & Remington, 2008; Hickey, McDonald, & Theeuwes, 2006). The N2pc is an enhanced negativity that is observed over posterior scalp electrodes contralateral to the side of an attended stimulus, is typically elicited between 200 and 300 msec after the onset of a visual search array, and is assumed to reflect the attentional selection of potentially relevant items among distractors in visual search tasks (Eimer, 1996; Luck & Hillyard, 1994). Eimer and Kiss (2008) measured the N2pc to spatially uninformative color singleton cues that preceded target search arrays. When observers had to report the orientation of a uniquely colored red target bar among gray distractor bars, behavioral spatial cueing effects indicative of attentional capture and an N2pc to red singleton cues were observed. In contrast, no behavioral cueing effects and no N2pc emerged in response to the same cues when observers had to detect a smaller target bar among larger distractor bars. The observation that an N2pc was elicited by perceptually salient color singleton cues only when color was task relevant supports the contingent involuntary attentional capture hypothesis by Folk et al. (1992) but is not in line with the view that capture is primarily driven by bottom-up salience (see also Eimer et al., 2009; Lien et al., 2008, for similar N2pc results in spatial cueing experiments). The absence of any early-onset N2pc components to color singleton cues that did not match the current top-down task set also casts doubt on the hypothesis that these cues trigger rapid salience-driven attentional capture,

which is later followed by rapid disengagement (Theeuwes, 2010; see also Ansorge, Kiss, Worschech, & Eimer, 2011, for further ERP evidence against this rapid disengagement account).

Although these ERP experiments provide no support for the existence of bottom-up attentional capture that is triggered independently of top-down task sets, it is notable that all employed variants of the spatial cueing paradigm introduced by Folk et al. (1992). In fact, very different findings were obtained in an ERP study that measured N2pc components in the additional singleton paradigm (Hickey et al., 2006). In this experiment, in which shape singletons served as targets and could be accompanied by salient but task-irrelevant color singleton distractors, RTs were delayed in distractor-present relative to distractor-absent trials. Most importantly, a reliable N2pc component was triggered by color singleton distractors on trials in which the target was on the vertical meridian (and therefore did not elicit lateralized selection-related ERP components), suggesting that these distractors did indeed capture attention in spite of the fact that they were known to be task irrelevant. Moreover, on trials in which targets and distractors were located in opposite hemifields, a small distractor N2pc preceded the target N2pc, suggesting that attention was initially drawn to the distractor before it was reallocated to the target. These results appear to provide strong support for the bottom-up nature of attentional capture by salient visual events and against the hypothesis that attentional capture is always under top-down control.

To summarize, recent ERP studies of attentional capture have, so far, failed to resolve the impasse between top-down and bottom-up accounts of attentional capture. Whereas N2pc results from spatial cueing experiments support the contingent involuntary attention hypothesis by Folk et al. (1992), N2pc evidence from the additional singleton paradigm points to an important and independent role for bottom-up salience in attentional capture. This is clearly a very unsatisfactory state of affairs, which hampers progress in this area. To rectify this situation, the factors that are responsible for the discrepant findings in spatial cueing and additional singleton studies need to be identified. One potentially critical and hitherto overlooked difference between these two experimental procedures concerns the specific time demands that are imposed on attentional selectivity. In experiments that employ the additional singleton paradigm, search displays typically remain visible until a response has been executed. As a consequence, participants have sufficient time to detect, select, and identify a target stimulus even when attention is initially drawn to a task-irrelevant but salient distractor. In contrast, cue and search arrays in spatial cueing experiments are presented very briefly and in rapid succession (with typical stimulus durations varying between 50 and 200 msec). This imposes much stricter temporal demands on attentional target selection, as the time window for detecting, selecting, and identifying a target is very narrow, and attentional capture by a

distractor will almost certainly result in the target stimulus being missed. In short, the allocation of attention to a task-irrelevant but salient stimulus will compromise successful target detection under conditions of high time pressure (short stimulus durations) but much less in tasks in which time pressure is low (long stimulus durations). In the former, but not in the latter case, efficient task performance may require the additional activation of mechanisms that prevent capture by salient distractors. The presence of salience-driven attentional capture effects in experiments with long search display durations (additional singleton task) and the presence of task-set-contingent attentional capture in experiments in which search display durations are short (spatial cueing task) may be the consequence of such differences in the time demands on attentional selectivity in these two experimental paradigms.

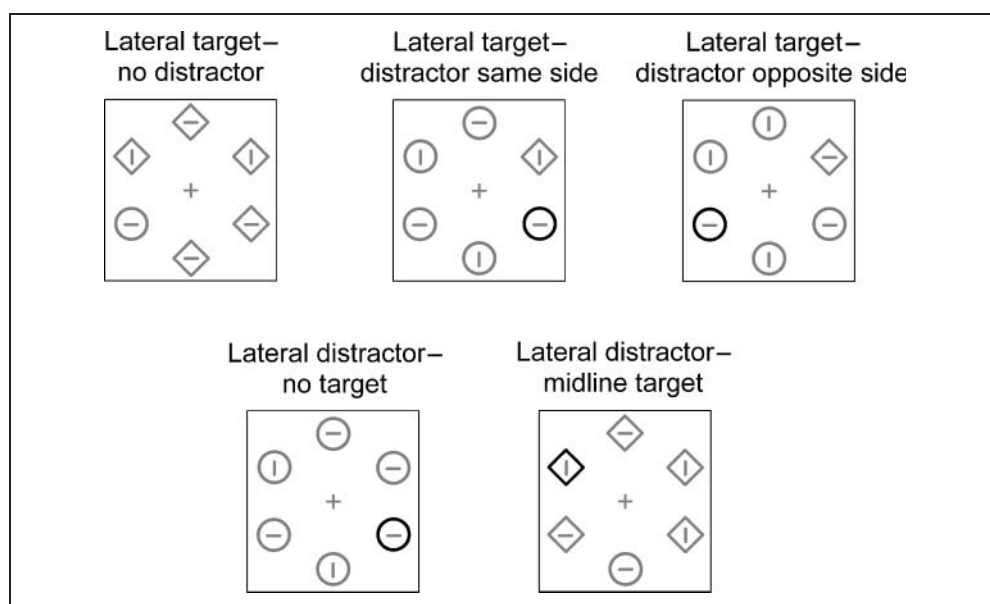
The aim of the present ERP study was to investigate the hypothesis that the presence versus absence of salience-driven attentional capture depends on the temporal demands of an attentional selection task. To test this, we employed the additional singleton paradigm. Experimental procedures were very similar to the previous ERP study by Hickey et al. (2006), which obtained N2pc evidence for attentional capture by salient but irrelevant distractors. Participants searched for a shape singleton target (a circle among diamonds or vice versa in randomly intermixed trials) and responded according to the orientation of the line within the target shape. Targets appeared with equal probability at any of the six array positions (see Figure 1). Twenty-five percent of all arrays did not contain a shape target singleton. The presence or absence of an additional task-irrelevant color singleton was blocked (as in Pinto, Olivers, & Theeuwes, 2005; Theeuwes, 1991, 1992). In one third of all blocks, no color singletons were presented. In the remaining blocks, each search array contained one color singleton (randomly red or green), which appeared

on the left or right side. Two experiments were conducted that were identical in all respects except for the duration of each search display. In Experiment 1, search arrays remained visible until a response was registered (as in Hickey et al., 2006). In Experiment 2, search display duration was limited to 200 msec. Target shape and distractor color always varied unpredictably across trials, as distractor-induced RT costs indicative of attentional capture are much larger under these conditions than in tasks in which target and/or distractor features are constant and, therefore, predictable (e.g., Becker, 2007; Pinto et al., 2005).

If attentional capture by salient but irrelevant color singletons is critically dependent on the temporal demands imposed on attentional selectivity, ERP evidence for salience-driven attentional capture should be observed in Experiment 1, but not in Experiment 2. When search arrays remained visible until response onset, color singleton distractors were expected to trigger an N2pc component indicative of attentional capture, in line with the results of Hickey et al. (2006). However, and critically, when display duration was limited to 200 msec, the prediction was that salience-driven attentional capture would be prevented by top-down control because of its potentially disastrous consequences for target detection and task performance. If this was the case, no N2pc should be triggered by color singletons in Experiment 2. Instead, lateralized posterior ERPs might provide evidence for the active inhibition of attention shifts to distractor singletons.

Top-down inhibition of attentional capture has recently been associated with a lateralized posterior ERP component that resembles the N2pc in terms of its latency and topography but shows an inverse polarity. This contralateral positivity (termed Pd component) was elicited by laterally presented color distractors when observers discriminated the shape of a luminance target on the vertical meridian (Hickey, Di Lollo, & McDonald, 2009) and was

**Figure 1.** Examples of search displays for the five trial types used in the N2pc analyses in both experiments. The color singleton distractor was either red or green (depicted here in black).



interpreted as reflecting the active inhibition of these distractors. The Pd was eliminated when observers were only required to detect the presence of a target, suggesting that distractors are suppressed only when attentional task demands are high. Sawaki and Luck (2010) reported Pd components to salient color distractors when observers searched for nonsalient target letters and proposed that salient singletons produce an automatic “attend-to-me signal” that can be overridden by active top-down suppression to avoid attentional capture by these stimuli. A Pd component has also been observed in the spatial cueing task in response to color singleton cues when participants searched for size-defined targets, and color was, therefore, task irrelevant (Eimer & Kiss, 2008). If attentional capture by irrelevant color distractors in the additional singleton task can be prevented by active inhibition when this is required by the temporal demands of an attentional selection task, a Pd component should be found for these stimuli in Experiment 2, in which search displays were presented for only 200 msec.

To test these hypotheses, lateralized posterior ERP components were measured in Experiments 1 and 2 for five different types of search arrays (see Figure 1). ERP components elicited in response to lateral shape target singletons were computed separately for arrays without an additional color distractor, and for arrays in which a color distractor was located on the same side as the target, or on the opposite side, respectively. For these arrays, strong target N2pc components should be found, but these were expected to be modulated by the presence of distractor-elicited N2pc or Pd components in Experiments 1 and 2. ERP components to lateral distractors were computed separately for target-absent displays, and for search arrays, in which targets appeared on the vertical midline and, therefore, did not trigger a lateralized N2pc component. The critical question was whether these distractors would elicit an N2pc component indicative of attentional capture in Experiment 1, and a Pd component indicative of suppressed capture in Experiment 2.

## METHODS

### Participants

Seventeen paid volunteers were recruited to participate in Experiment 1, and 16 new volunteers were recruited for Experiment 2. Informed consent was obtained from all participants before testing. Four participants of Experiment 1 and three of Experiment 2 were excluded from analyses because of excessive eye movements (see Methods section). One additional participant was excluded from each experiment because of excessive alpha activity. The remaining 12 participants in Experiment 1 (four men) had a mean age of 25.7 years. The 12 participants in Experiment 2 (four men) had a mean age of 29.1 years. All were right-handed and had normal or corrected vision.

### Stimuli and Procedure

Stimulus presentation and response collection were controlled using E-Prime software (Psychology Software Tools, Inc., Sharpsburg, PA). Stimuli were presented on a CRT monitor with a 100-Hz refresh rate. Each search array consisted of six outline shapes placed at regular intervals around a central fixation cross at a radial distance of  $4.0^\circ$ . One of these shapes was a singleton item (a circle among diamonds or a diamond among circles; see Figure 1). Each outline shape subtended  $1.1^\circ \times 1.1^\circ$  and enclosed a line segment whose orientation (horizontal or vertical) was randomly assigned. All items in the display were light gray (Commission Internationale de l'Éclairage [CIE] chromaticity coordinates, 0.287/0.314) except for the irrelevant color singleton, which (when present) was either red (CIE, 0.619/0.339) or green (CIE, 0.296/0.567). All colors were equiluminant ( $10.3 \text{ cd/m}^2$ ), and all stimuli were presented against a black background. In Experiment 1, search arrays remained present until a response was registered, up to a maximum of 2500 msec. In Experiment 2, each search array was presented for 200 msec and was followed by a fixation cross display for 2300 msec. In all other respects, stimuli and procedure were identical in both experiments.

Shape singletons (circles among diamonds or vice versa) appeared randomly and equiprobably at one of the six possible locations in 75% of all trials. In the remaining 25% of all trials, the shape of all display items was uniform. Shape singletons served as targets, and participants were instructed to report the orientation of the line (horizontal or vertical) within the target shape by pressing one of two vertically aligned buttons with their left or right index finger. Orientation-to-response-key mapping was counter-balanced across participants. No response was required on target-absent trials. In one third of all blocks, no color singletons were presented. In the other blocks, one color singleton (randomly red or green) was present in every trial and appeared with equal probability at one of the four lateral positions (with the exception that target singleton shapes were never colored) but never at the top or bottom position. A total of 30 blocks with 32 trials per block were run. Two successive blocks with color singleton distractors alternated with one block without these distractors. Six participants started with two distractor-present blocks, and the other six started with a distractor-absent block.

### EEG Data Recording and Analysis

EEG was DC-recorded from 23 electrodes mounted in an elastic cap at positions Fpz, Fz, F3, F4, F7, F8, FC5, FC6, Cz, C3, C4, T7, T8, CP5, CP6, Pz, P3, P4, P7, P8, PO7, PO8, and Oz. EEG data were sampled at 500 Hz, with a digital low-pass filter of 40 Hz. All electrodes were referenced to the left earlobe and off-line rereferenced to averaged earlobes. The continuous EEG was segmented from 100 msec before to 500 msec after search array onset. Incorrect trials and trials containing saccades (horizontal EOG exceeding

$\pm 25 \mu\text{V}$ ), blinks (Fpz exceeding  $\pm 60 \mu\text{V}$ ), or muscle artifacts (all other electrodes exceeding  $\pm 80 \mu\text{V}$ ) were removed from further analyses. Three participants were excluded because their residual horizontal EOG exceeded  $\pm 4 \mu\text{V}$  in at least one trial condition. Average waveforms were computed separately for five different types of search stimulus arrays: (1) lateral target, no distractor; (2) lateral target, distractor same side; (3) lateral target, distractor opposite side; (4) lateral distractor, no target; and (5) lateral distractor, midline target. Separate averages were computed for trials in which targets appeared in the left or right hemifield. For trials with lateral distractors and absent or midline targets, separate averages were computed for left and right distractors. To compute lateralized posterior ERP components (N2pc, Pd), mean amplitude values were measured at lateral posterior electrodes PO7 and PO8. Separate repeated measures ANOVAs were conducted to examine N2pc/Pd components in response to lateral target stimuli (with distractors either absent, on the same side, or on the opposite side), and in response to lateral distractors (with targets either absent or on the vertical midline). The former analyses included the factor Distractor Type (absent vs. same side vs. opposite sides), and the latter included the factor Target Type (absent vs. midline). Both analyses also included the factors Contralaterality (electrode contralateral vs. ipsilateral to target/distractor location) and Target/Distractor Side (left vs. right). Greenhouse–Geisser corrections were used for main effects and interactions where appropriate. Performance differences between conditions were assessed with two-tailed  $t$  tests.

## RESULTS

### Experiment 1

#### *Behavioral Results*

Trials in which responses were faster than 200 msec or slower than 2400 msec were excluded from analyses (less than 0.1% of all trials). The presence of a color singleton distractor delayed mean correct RTs to shape targets (993 vs. 912 msec;  $t(11) = 6.7, p < .001$ ), and the size of this distractor interference effect on distractor-present trials was modulated by the relative position of targets and distractors. RTs were delayed on trials in which targets and distractors appeared in the same hemifield relative to trials in which they were in opposite hemifields (1024 msec vs. 949 msec;  $t(11) = 7.8, p < .001$ ). Mean RT for targets on the vertical meridian in distractor-present blocks was 1005 msec, that is, intermediate between same-hemifield and opposite-hemifield trials (both  $t(11) > 2.3$ , both  $ps < .05$ ). RT distractor interference effects were smallest on trials in which targets and distractors appeared on opposite sides but were still reliable relative to distractor-absent blocks ( $t(11) = 2.6, p < .05$ ). Error rates were higher in blocks with color singleton distractors than in blocks in which targets were presented without distractors (4.1%

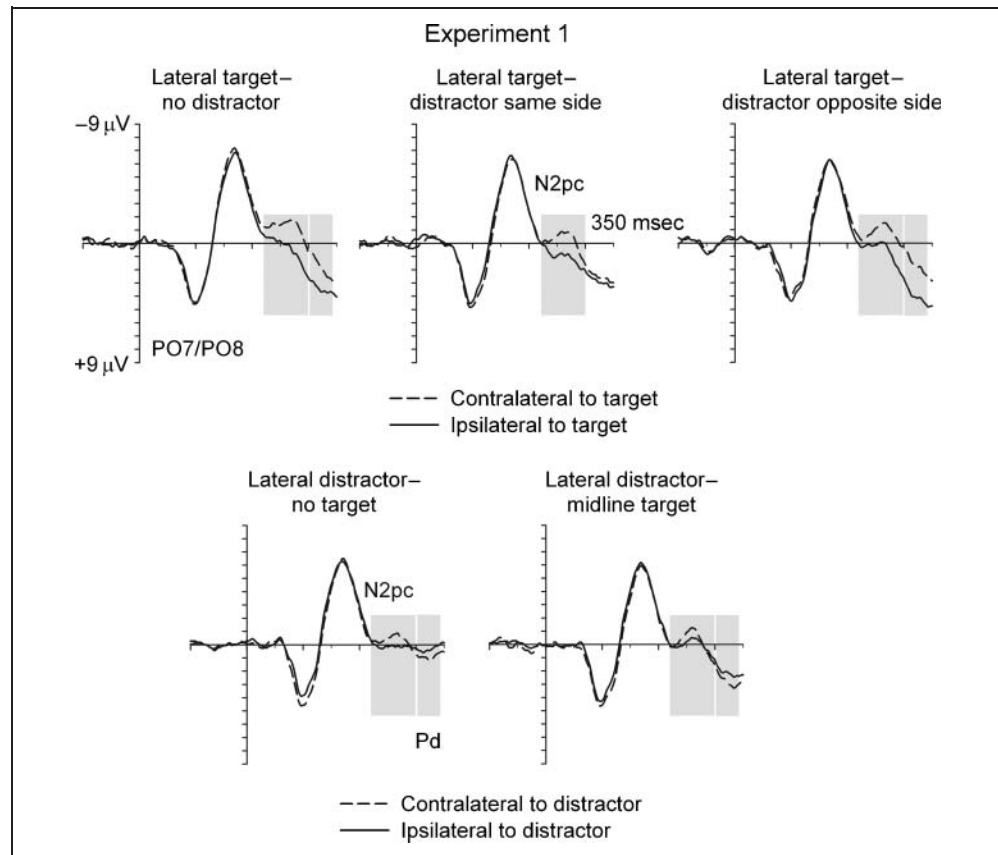
vs. 2.9%;  $t(11) = 2.9, p < .05$ ). False alarms occurred on 0.4% of all target-absent trials.

#### *ERP Results*

Figure 2 (top row) shows ERPs triggered at electrodes PO7/PO8 by lateral shape targets for search arrays representing the three levels of the factor distractor type (arrays without a color singleton distractor, arrays with a target and distractor in the same hemifield, and arrays with a target and distractor in opposite hemifields). Figure 2 (bottom row) shows ERPs for trials with lateral color distractors, which were either presented without target or with a shape target on the vertical meridian (representing the two levels of the factor target type in the analysis of distractor-elicited ERPs). As expected, an N2pc was triggered by lateral shape targets. Importantly, an N2pc of smaller amplitude and reduced duration was also observed for lateral color singleton distractors, both on target-absent trials and on trials with shape targets on the vertical meridian. This distractor N2pc was followed by an enhanced positivity contralateral to the distractor that started around 300 msec after search array onset, indicative of the Pd component. During this time interval, target N2pc amplitudes were strongly attenuated on trials with same-side distractors relative to trials with targets and distractors on opposite sides. To capture this specific sequence of lateralized posterior ERP components, mean amplitudes at PO7/PO8 were analyzed within two successive time windows, one focused on the N2pc component (220–300 msec after search array onset) and the other one focused on the subsequent Pd component (300–340 msec poststimulus).

*Lateralized posterior ERP components triggered by target stimuli.* In the 220–300 msec time window, a main effect of Contralaterality was present,  $F(1, 11) = 30.8, p < .001$ , reflecting the presence of target-elicited N2pc components. There was no interaction between Contralaterality and Distractor Type,  $F < 1.1$ , because of the fact that N2pc amplitudes, triggered by targets during this time interval, were similar regardless of whether distractor stimuli were absent, appeared on the same side, or appeared on the opposite side. In the 300–340 msec time window, a main effect of Contralaterality,  $F(1, 11) = 11.6, p < .01$ , was accompanied by an interaction between Contralaterality and Distractor,  $F(2, 22) = 7.1, p < .05$ . As can be seen in Figure 2 (top row), the late phase of the target N2pc was strongly attenuated on trials in which targets and distractors appeared on the same side relative to opposite side and distractor-absent trials,  $F(1, 11) = 7.7$  and  $14.2$ , both  $ps < .05$ . This was confirmed in follow-up analyses that revealed the presence of reliable late target N2pc components on distractor-absent trials,  $F(1, 11) = 10.0, p < .01$ , and on trials in which distractors appeared in the opposite hemifield,  $F(1, 11) = 22.8, p < .001$ , but not on trials in which targets and distractors were located in the same hemifield,  $F < 1$ .

**Figure 2.** Grand-averaged ERPs at posterior electrodes PO7/PO8 contralateral and ipsilateral to the location of the target (top) when the distractor singleton was absent (left), when the distractor singleton was in the same hemifield (middle), and when it was in the opposite hemifield (right) and to the location of the distractor singleton (bottom) in target-absent trials (left) and in trials when the target was on the vertical meridian (right) in Experiment 1.



*Lateralized posterior ERP components triggered by distractor stimuli.* A main effect of Contralaterality,  $F(1, 11) = 5.4, p < .05$ , was observed in the 220-300 msec poststimulus time window, demonstrating that color singleton distractors triggered a reliable N2pc component. There was no interaction between Contralaterality and Target Presence,  $F < 1.1$ , suggesting that this distractor N2pc was of similar size regardless of whether distractors were the only singleton item in the search array or were presented together with a shape singleton target on the vertical meridian. In the subsequent 300-340 msec post-stimulus time window, a reliable main effect of Contralaterality was present,  $F(1, 11) = 4.8, p < .05$ , now reflecting a contralaterally enhanced positivity (Pd). There was no interaction between Contralaterality and Target Presence,  $F < 1$ , as distractor Pd amplitudes did not differ between trials without targets and trials with targets on the vertical midline.

## Experiment 2

### Behavioral Results

Trials in which responses were faster than 200 msec or slower than 2400 msec were excluded from analyses (less than 0.1% of all trials). As in Experiment 1, mean correct RTs to targets were slower in blocks with color singleton distractors than in blocks without color distractors (924 msec

vs. 875 msec;  $t(11) = 6.5, p < .001$ ). This distractor interference effect was again affected by the relative position of targets and distractors. Slower RTs were observed for trials in which targets and distractors appeared in the same hemifield than for trials in which they were located in opposite hemifields (959 msec vs. 893 msec;  $t(11) = 5.9, p < .001$ ). Mean RT to targets on the vertical meridian (and distractors on the left or right side) was 921 msec, which was significantly slower than RTs on same-hemifield trials and faster than RTs on opposite-hemifield trials (both:  $t(11) > 3.6, p < .01$ ). Importantly, the size of the distractor-induced RT interference effect in Experiment 2 was significantly smaller than in Experiment 1 (49 msec vs. 81 msec;  $F(1, 22) = 4.7, p < .05$ ). As in Experiment 1, this effect was smallest on trials in which targets and distractors appeared on opposite sides, where it only approached significance when compared with distractor-absent blocks ( $t(11) = 1.9, p = .09$ ). Error rates on target-present trials were higher in blocks with color distractors relative to distractor-absent blocks (5.8% vs. 4.6%;  $t(11) = 2.7, p < .05$ ). False alarms occurred on 0.6% of all target-absent trials.

### ERP Results

Figure 3 (top row) shows ERPs elicited at electrodes PO7/PO8 in response to search arrays with a shape target

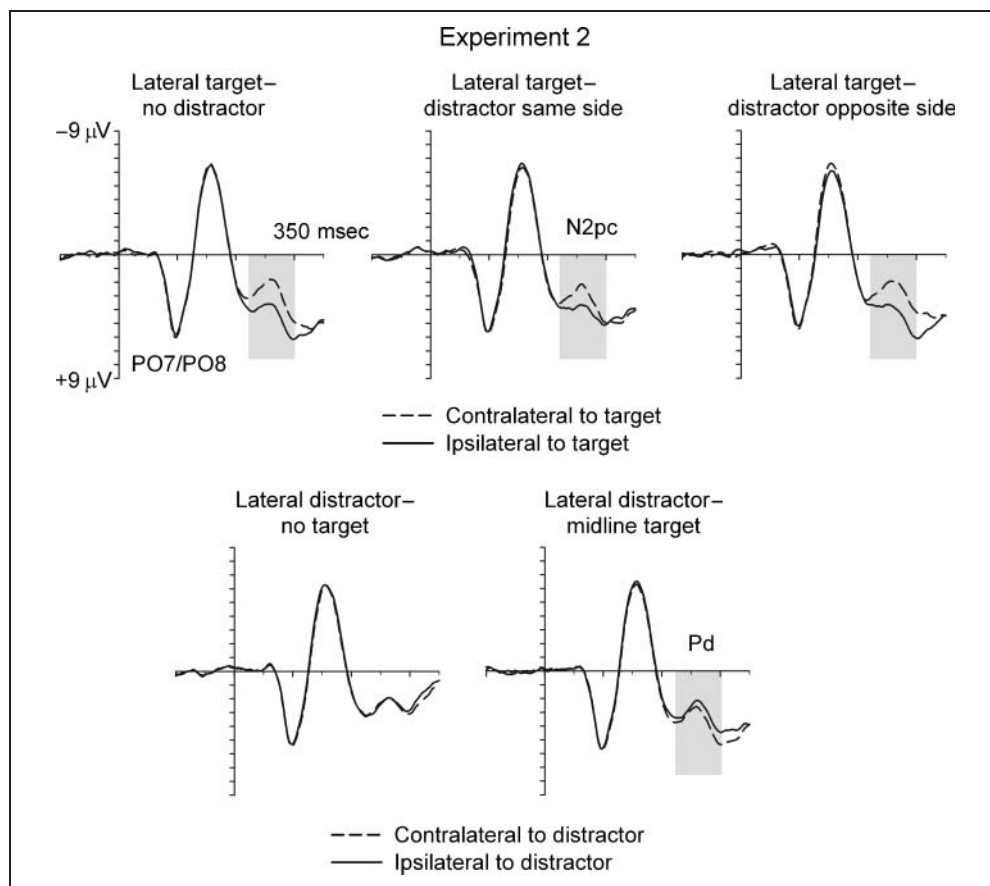
stimulus on the left or right side, on trials without a color singleton distractor, and on trials in which shape targets were accompanied by a distractor in the same hemifield or on the opposite side. Figure 3 (bottom row) shows ERP waveforms to search arrays that included a color singleton distractor on the left or right side, on trials in which no shape target was present, and on trials in which a shape target was located on the vertical meridian. As in Experiment 1, a pronounced N2pc was triggered in response to search arrays that contained a lateral target stimulus. However, and in marked contrast to Experiment 1, no N2pc was elicited by lateral color singleton distractors. Instead, a contralateral positivity (Pd) was observed in the N2pc time interval on trials in which a lateral distractor was accompanied by a midline target. These observations were confirmed by analyses of ERP mean amplitudes obtained at PO7/PO8 in the 220–300 msec poststimulus interval.

*Lateralized posterior ERP components triggered by target stimuli.* A main effect of Contralaterality was present,  $F(1, 11) = 22.8, p < .001$ , demonstrating the presence of reliable N2pc components in response to target stimuli (Figure 3, top row). There was also an interaction between Contralaterality and Distractor Type,  $F(2, 22) = 6.2, p < .01$ , as N2pc amplitudes were smaller on trials in which targets

and distractors appeared on the same side as compared with opposite-side trials and distractor-absent trials. Two follow-up analyses compared N2pc amplitudes on same-side trials to amplitudes on opposite-side and distractor-absent trials, respectively, with the Distractor Type (same-side vs. opposite-side trials and same-side vs. distractor-absent trials) as additional factor. Interactions between Contralaterality and Distractor Type were found in both analyses,  $F(1, 11) = 8.6$  and  $7.3$ , both  $ps < .05$ , respectively, confirming that the N2pc amplitude on same-side trials was reliably reduced relative to opposite-side and distractor-absent trials. Analyses conducted separately for each distractor-type array revealed that a reliable N2pc was triggered in response to targets not only in trials in which distractors were absent,  $F(1, 11) = 21.4, p < .001$ , and in trials with a distractor in the opposite hemifield,  $F(1, 11) = 21.4, p < .001$ , but also in trials in which targets and distractors appeared in the same hemifield,  $F(1, 11) = 14.3, p < .01$ .

*Lateralized posterior ERP components triggered by distractor stimuli.* The analysis of ERP mean amplitudes obtained in the 220–300 msec poststimulus time window in response to search arrays that contained lateral distractors without targets or with targets on the vertical midline (Figure 3, bottom row) obtained a significant main effect of contralaterality,  $F(1, 11) = 5.2, p < .05$ , and, importantly,

**Figure 3.** Grand-averaged ERPs at posterior electrodes PO7/PO8 contralateral and ipsilateral to the location of the target (top) when the distractor singleton was absent (left), when the distractor singleton was in the same hemifield (middle), and when it was in the opposite hemifield (right) and to the location of the distractor singleton (bottom) in target-absent trials (left) and in trials when the target was on the vertical meridian (right) in Experiment 2.



an interaction between Contralaterality and Target Presence,  $F(1, 11) = 11.6, p < .01$ . A significant contralaterally enhanced positivity (Pd) was triggered in response to distractors that were accompanied by a target on the midline,  $F(1, 11) = 11.6, p < .01$ , whereas no lateralized effect was present for lateral color singleton distractors in the absence of a target stimulus,  $F < 1$ .

## DISCUSSION

Is rapid attentional capture by salient but task-irrelevant singleton stimuli a bottom-up phenomenon that is exclusively driven by salience signals and is unaffected by current task sets, or is this type of attentional capture accessible to top-down control? Although ample behavioral and ERP evidence for the task set contingent nature of attentional capture has been found in spatial cueing experiments, results from the additional singleton task have, so far, provided apparently robust support for bottom-up capture. The results of the present study demonstrate that, even in this task, salience-driven singleton capture is not triggered in an entirely automatic bottom-up fashion but can be prevented by top-down control when this is required by the temporal demands of an attentional task.

We recorded lateralized posterior ERP components in response to visual search arrays that could contain a shape-defined singleton target and/or a task-irrelevant color singleton. In Experiment 1, search arrays remained visible until response onset, whereas display duration was limited to 200 msec in Experiment 2. The ERP results of Experiment 1 demonstrated that color singletons captured attention, although they were known to be task-irrelevant. When these singleton distractors appeared on the left or right side, an N2pc component was elicited, both on trials in which they were accompanied by a shape-defined target on the vertical midline and on trials in which they were the only singleton in the display. The presence of an N2pc to irrelevant color singletons mirrors previous findings by Hickey et al. (2006) and confirms that these stimuli can capture attention when search displays remain visible until response onset. In marked contrast, no N2pc was elicited by physically identical color singletons in Experiment 2, in which search arrays were visible for only 200 msec. Instead, an enhanced contralateral positivity (Pd) was observed in response to these stimuli on trials in which they were accompanied by a shape target on the vertical midline. The Pd component has previously been interpreted as an ERP marker of top-down inhibition of attentional capture (Sawaki & Luck, 2010; Hickey et al., 2009). Its presence in Experiment 2 therefore suggests that, when the temporal demands on attentional selectivity are increased, participants can successfully inhibit attentional capture by salient but task-irrelevant singletons. In target-absent trials, no lateralized posterior ERP modulation was elicited by color distractors in Experiment 2, which again contrasts with Experiment 1,

in which a reliable N2pc component was observed on these trials.

To confirm the central finding that the pattern of lateralized posterior ERP activity triggered by salient color distractors in the N2pc time range is determined by temporal demands of an additional singleton task, two further analyses compared lateralized ERPs obtained at PO7/PO8 in the 220–300 msec time window on target-present and target-absent trials across both experiments, with the additional between-subject factor display duration (long, Experiment 1; short, Experiment 2). A significant interaction between display duration and contralaterality was obtained for trials with lateral color distractors and midline targets,  $F(1, 22) = 9.4, p < .01$ , reflecting a distractor-triggered N2pc in Experiment 1 and a Pd in Experiment 2. This interaction was also reliable for target-absent trials with lateral distractors,  $F(1, 22) = 5.5, p < .05$ , reflecting the presence of a distractor N2pc in Experiment 1 and its absence in Experiment 2.

In Experiment 1, the N2pc to color singleton distractors was followed by a lateralized posterior ERP modulation of opposite polarity that started 300 msec after search array onset (see Figure 2) and is likely to reflect a late-onset Pd component. The presence of a Pd that was preceded by an N2pc suggests a temporal sequence of attentional capture by salient distractors that is followed by active top-down inhibition (similar to the scenario suggested by Theeuwes, 2010). Notably, a similar pattern of an N2pc followed by a Pd component was also present in the study by Hickey et al. for search arrays with lateral distractors and midline targets (Hickey et al., 2006, Figure 3B), although no statistical analyses of time windows beyond the N2pc were reported. It is plausible to assume that, after the initial distractor-triggered attentional capture under conditions of low temporal task demands, the subsequent reallocation of attention toward the target location involves the active inhibition of distractor locations and that this is reflected in a late Pd component that follows the N2pc.

As expected, lateral shape singleton targets elicited a robust N2pc component in both experiments, reflecting attentional selection of these task-relevant stimuli. This was the case regardless of whether targets appeared without a color singleton distractor, with a distractor on the same side, or with a distractor on the opposite side. Notably, even in Experiment 1 in which distractors triggered an N2pc indicative of attentional capture on target-absent trials and on trials with midline targets, ERPs to search arrays with a lateral target and a color distractor in the opposite hemifield revealed no evidence that salience-driven attentional capture by color singletons was triggered before the attentional selection of shape targets. In contrast to previous findings by Hickey et al. (2006), there was no early distractor-elicited N2pc that preceded the target N2pc, suggesting that even under conditions of low time pressure, there was a consistent net attentional bias toward the hemifield that contained the shape target. In both experiments, there were target N2pc amplitude differences



between search displays with target and distractor singletons on the same or on different sides, and these can be accounted for by the simultaneous presence of an early or late Pd to color distractors. Because N2pc and Pd components have opposite polarity, the net lateralized posterior activity will be smaller on trials in which target and distractor singletons are presented on the same side than on trials in which they appear in opposite hemifields. This was indeed the case in Experiment 2, in which distractors triggered a Pd in the N2pc time range on target-present trials, and target N2pc amplitude was reduced on same-side trials. Similarly, in Experiment 1, in which distractors triggered a late-onset Pd that followed the N2pc, the target N2pc was less sustained on same-side than on opposite-side trials (see Figure 2).

The presence of systematic differences between distractor-triggered lateralized posterior ERP components observed in these two experiments demonstrates that temporal demands on attentional selectivity have a strong impact on the processing of salient distractor singletons. These stimuli triggered attentional capture with long-duration search displays in Experiment 1, as reflected by an N2pc, whereas capture was inhibited for the short-duration displays in Experiment 2, as indicated by the Pd component. Links between inhibitory top-down control and distractor-induced attentional capture in the additional singleton paradigm are also suggested by the results of a recent fMRI study by Leber (2010). In this study, the magnitude of distractor interference effects could be predicted by measuring pre-trial activation in left middle frontal attentional control regions, in line with the hypothesis that these areas mediate resistance to attentional capture by salient but irrelevant visual stimuli.

If capture was successfully prevented in Experiment 2, why was there still a substantial distractor interference effect (i.e., an RT difference between distractor-present and distractor-absent trials) of nearly 50 msec? Although such distractor-elicited RT costs are usually interpreted as reflecting bottom-up attentional capture followed by the time-consuming process of reallocating attention to the target location, the spatial distribution of behavioral interference effects does not support this interpretation. These effects were strongly modulated by the relative positions of target and distractor singletons, as they were largest in trials in which both appeared in the same hemifield, intermediate on trials with lateral distractors and midline targets, and smallest on trials in which these two singletons were located in opposite hemifields (see also Mathôt, Hickey, & Theeuwes, 2010; Hickey et al., 2006, for analogous results). If behavioral distractor interference effects exclusively reflected capture and subsequent re-orienting of attention, the opposite pattern should have been observed, as attention shifts to the target should require less time when attention has already been moved to a nearby location in the same hemifield than when it was attracted by a distractor on the opposite side. The presence of stronger interference by nearby distractors may instead

reflect competitive interactions between targets and salient distractors, which are typically larger for stimuli that are in close spatial proximity than for stimuli in opposite hemifields (Mathôt et al., 2010; Mounts & Gavett, 2004). To enable the selection of task-relevant visual events, this competition needs to be resolved by top-down biases in favor of targets and/or against distractors (Desimone & Duncan, 1995). The observation that distractor interference effects were smaller in Experiment 2 than in Experiment 1, although stimulus arrays were physically identical, strongly suggests that such top-down biases were more effective when temporal task demands were high, presumably because of additional location-specific distractor inhibition. The fact that substantial distractor interference effects remained present in Experiment 2 indicates that suppression of distractor-elicited capture only attenuated, but did not completely eliminate, attentional competition between target and distractor singletons. Such considerations also suggest a modified concept of filtering costs induced by salient but task-irrelevant singletons. Filtering costs have previously been attributed to early stages of perceptual encoding before selective attentional processing (Folk & Remington, 1998). If salient singleton distractors are subject to inhibition when temporal task demands are high, behavioral filtering costs might instead arise as a consequence of competitive interactions between targets and distractors that are modulated by top-down inhibitory control (see also Becker, 2007, for a more detailed discussion of links between filtering costs and distractor inhibition).

One final notable result of the present study was the observation that an early-onset Pd component was observed in Experiment 2 for search arrays with lateral distractors and midline targets, whereas no lateralized posterior ERP component was triggered at all on trials in which these distractors appeared without a shape target (Figure 3, bottom). If high temporal task demands resulted in a rapid top-down inhibition of salient color singleton distractors, as argued before, one would assume that this process will be triggered regardless of whether a shape-defined target is also present in the display. The observation that a reliable Pd component was only observed on trials with midline targets may suggest that distractor inhibition is not triggered unconditionally but only after a rapid preattentive analysis of the search display has uncovered evidence for the presence of a target. Active inhibition would then only be applied to distractors in trials in which they compete for attention with a simultaneously present target. It should, however, be noted that the absence of lateralized posterior modulations for averaged target-absent ERPs does not prove the absence of distractor capture or distractor inhibition on single trials. If these two processes were elicited on an approximately equal number of trials, the associated N2pc and Pd components would cancel each other out, resulting in no overall difference in averaged ERP waveforms. Although the dependency of an early-onset Pd on the presence of a target observed in Experiment 2 is intriguing, the

functional significance of this observation will have to be clarified in future experiments.

The conclusion from the present study that the ability of salient but currently irrelevant visual stimuli to capture attention in the additional singleton paradigm depends on temporal task demands is in line with observations from other recent experiments. For example, Sawaki and Luck (2010) found a distractor-elicited Pd component indicative of top-down inhibition under conditions in which search display duration was short (200 msec). In a recent behavioral study of memory-driven attentional capture from our laboratory (Dalvit & Eimer, 2011), participants memorized a color for subsequent recall before searching for a shape singleton target that was presented together with an irrelevant color singleton distractor, which either matched or did not match the memorized color. RTs were delayed on trials with memory-matching distractors, reflecting memory-driven attentional capture. Critically, this effect was much larger in blocks in which search displays remained visible until response onset than in blocks in which search arrays were presented for only 200 msec (53 msec vs. 17 msec), in line with the hypothesis that search can be prioritized and shielded from interactions with working memory when this is required by high temporal task demands. In blocks in which display duration was randomized and thus unpredictable, RT costs for trials with memory-matching distractors did not differ between long and short displays, demonstrating that these costs are not determined by display duration as such but, instead, by top-down search strategies that are linked to known temporal task demands.

In summary, the results of the current study provide new evidence that, even in the additional singleton task, attentional capture by salient but task-irrelevant stimuli is not a purely bottom-up phenomenon that is inaccessible to top-down processing strategies. Salient distractors will indeed capture attention under conditions in which this does not prevent the subsequent successful selection of task-relevant targets. However, when search arrays are presented very briefly, so that distractor-triggered attentional capture will increase the likelihood that target stimuli are missed, salience-driven capture can be actively inhibited by top-down control.

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