



Active suppression of salient-but-irrelevant stimuli does not underlie resistance to visual interference

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ABSTRACT

In visual search for a shape target, interference from salient-but-irrelevant color singletons can be resisted in feature search mode, but not in singleton detection mode. In singleton detection mode, we observed a contralateral positivity (P_D) after 260–340 ms, suggesting that the salient distractor was suppressed. Because RTs in singleton detection mode increased when a distractor was present, we conclude that active suppression of distractors takes time. In feature search mode, no increase in RTs and no P_D to the distractor was observed, showing that resistance to interference was not accomplished by suppression. Rather, the smaller N2pc to the target in feature search than in singleton detection mode suggests that enhancement of target features avoided interference. Thus, the strong top-down set in feature search mode eliminated the need to suppress the early attend-to-me signal (corresponding to the Ppc, from 160 to 210 ms) that was generated by salient stimuli independently of search mode.

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1. Introduction

In some advertisement campaigns, the advertised product is the only colored object in an otherwise black-and-white picture. The creative minds behind these campaigns followed their intuition that observers' attention would be drawn to the colored stimulus. Research on visual selective attention provides evidence that this strategy may work even against the intentions of the observer. In the additional singleton paradigm (Theeuwes, 1991), participants were asked to search for a shape that was different from the remaining shapes in the display (i.e., a shape singleton). On 50% of the trials, all stimuli had the same color whereas on the other 50% of the trials, one of the nontarget elements had a different color (i.e., a color singleton). The presence of a color singleton increased search times for the shape singleton although color was completely irrelevant for the task. The interpretation by Theeuwes (1991, 2010) was that the color singleton captured attention. According to this view, the initial attentional selection is based on saliency. That is, attention selects the object that stands out most from its visual context.

1.1. Singleton detection and feature search mode

The view that attention is controlled in a bottom-up manner by characteristics of the stimulus was opposed by the view that attentional control is top-down (e.g., Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992) (for review, see Lamy, Leber, & Egeth, 2012). According to Bacon and Egeth (1994), the distractor effect in the additional singleton paradigm arises because participants did not search for a particular target feature, but for any odd element. While this singleton detection strategy was feasible on distractor absent trials, it led to the erroneous selection of the color singleton on distractor present trials. Correcting for the wrong selection explains the longer RTs. To isolate the singleton detection strategy, Bacon and Egeth (1994) used a singleton shape target that varied unpredictably from trial to trial while the shape of nontarget elements did not change (see Fig. 1). Thus, participants could not focus on any particular shape, but had to search for the odd shape. To isolate search for a particular feature (i.e., feature search mode), they mixed various shapes into the search display so that the shape target was no longer a singleton. As a result, interference from the color distractor disappeared, demonstrating that the top-down set determines whether interference occurs. We refer to the absence of behavioral interference from salient distractors in feature search mode as **resistance to interference**.

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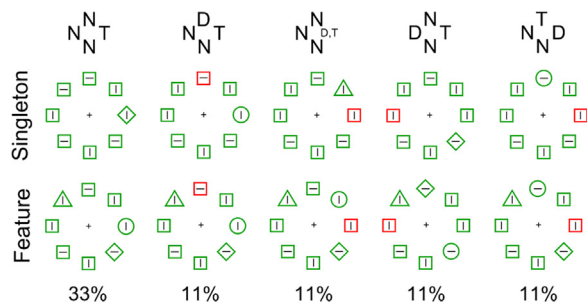


Fig. 1. Examples of experimental stimuli in singleton detection and feature search modes. Insets in row 1 show the schematic target (T), distractor (D), and nontarget (N) positions. In singleton detection mode, participants searched for a randomly changing shape (diamond, circle, or triangle, see row 2) that was a singleton among uniform nontargets. In feature search mode, participants searched for a circle among various nontarget shapes (see row 3). Here, we presented the target and distractor mostly at the top and on the right, but in the experiment, stimulus positions were randomized. The prevalence of each configuration as percentage of the total number of trials is shown at the bottom.

It should be noted that the original additional singleton paradigm allows for both search strategies. [Bacon and Egeth \(1994\)](#) stressed that observers may have used singleton detection because the target was a shape singleton. However, the target shape never changed so that in principle, observers could have used feature search. Whether observers use singleton detection or feature search may depend on previous exposure to singleton detection or feature search. [Leber and Egeth \(2006\)](#) showed that participants who were trained in singleton detection mode (with variable targets and uniform nontargets) showed interference in a subsequent test with the additional singleton paradigm. In contrast, participants who were trained in feature search mode (with fixed target and heterogeneous nontargets) did not show interference in the additional singleton paradigm. Thus, both strategies are available in the additional singleton paradigm (see also [Lamy & Egeth, 2003](#)).

1.2. Mixed- and fixed-feature search

[Hickey, McDonald, and Theeuwes \(2006\)](#) were the first to investigate the deployment of attention to salient-but-irrelevant color singletons in the additional singleton paradigm using electrophysiology. They focused on the N2pc, a negative deflection occurring contralateral to the attended stimulus at posterior sites ([Eimer, 1996; Luck & Hillyard, 1994](#)). By placing the distractor on a lateral position and the target on the vertical midline above or below central fixation (see [Woodman & Luck, 2003](#)), they were able to measure attentional capture by the distractor. [Hickey et al. \(2006\)](#) reported an N2pc to lateral distractors with midline targets, confirming attentional capture by salient stimuli. In their study, target and nontarget shapes were randomly swapped so that participants could not focus on a specific target shape. That is, on one trial, the target may have been a circle among diamonds, but on the subsequent trial, the target may have been a diamond among circles. We refer to this paradigm as the mixed-feature version of the addi-

tional singleton paradigm (see [Theeuwes, 1991](#)). An overview of the different search tasks is provided in [Table 1](#).

Some studies replicated the N2pc to salient distractors in mixed-feature search ([Burra & Kerzel, 2013; Kiss, Grubert, Petersen, & Eimer, 2012](#)), in particular on trials after target and distractor shapes swapped ([Hickey, Olivers, Meeter, & Theeuwes, 2011](#)), but others failed to do so ([McDonald, Green, Jannati, & Di Lollo, 2013](#)). Instead, [McDonald et al. \(2013\)](#) observed a contralateral deflection of opposite polarity in distractor-present trials with short RTs. The contralateral positivity is referred to as P_D and occurs in the same time range as the N2pc ([Burra & Kerzel, 2013; Hickey, Di Lollo, & McDonald, 2009; Kiss et al., 2012](#)) or follows the N2pc ([Feldmann-Wüstefeld & Schubö, 2013; Hilimire, Mounts, Parks, & Corballis, 2011; Sawaki & Luck, 2012](#)). The interpretation of the P_D occurring in the N2pc time range was that it reflects the suppression of irrelevant-but-salient stimuli, and the interpretation of the P_D occurring after the N2pc was that it reflects the active termination of a shift of attention.

While there is some disagreement on the presence of the P_D to salient-but-irrelevant stimuli in the mixed-feature version of the additional singleton paradigm (see [Theeuwes, 1991](#)), the P_D was more reliably observed in the fixed-feature version (see [Theeuwes, 1992](#)) where the target and nontarget shapes do not swap, but are fixed throughout the experiment. [Jannati, Gaspar, and McDonald \(2013\)](#) reported a P_D to the color distractor on trials with short RTs and [Burra and Kerzel \(2013\)](#) reported a P_D for all trials.

Further, a P_D to salient distractors occurred in mixed-feature search when the search display of the additional singleton paradigm was only briefly flashed for 200 ms ([Kiss et al., 2012](#)), suggesting that suppression of salient-but-irrelevant stimuli occurred when attentional selection had to occur rapidly (see also [Feldmann-Wüstefeld, Uengoer, & Schubö, 2015](#)). In general, divergent results were reported in studies with briefly flashed stimuli and fixed-feature search that did not use geometrical shapes as nontarget elements, but a large array of vertical lines that resemble a visual texture or pattern. [Töllner, Müller, and Zehetleitner \(2012\)](#) and [Wykowska and Schubö \(2010\)](#) reported no lateralized ERP to salient color distractors (but see [Feldmann-Wüstefeld & Schubö, 2013](#)), but an increase in the latency of the N2pc to the target when the distractor was present. Because we used geometrical shapes and unlimited viewing time in the present study, we derive our predictions from studies using these parameters.

Overall, the P_D appears to be associated with conditions that favor efficient target selection and rapid suppression of irrelevant stimuli. Most important, the P_D to salient distractors occurred reliably in fixed-feature search where RTs were short and interference from distractors was small, presumably thanks to active suppression of the distractor ([Burra & Kerzel, 2013; Jannati et al., 2013; Lamy & Yashar, 2008; Pinto, Olivers, & Theeuwes, 2005](#)). In contrast, an N2pc to salient distractors was only observed in mixed-feature search where RTs were long and interference from distractors was large, most likely due to attentional capture by the distractor ([Burra & Kerzel, 2013; Hickey et al., 2006; Hilimire & Corballis, 2014; Kiss et al., 2012](#)).

Table 1

Characterization of the different search tasks and the corresponding behavioral and electrophysiological observations. The shape of the singleton target varied across trials in mixed-feature search and singleton detection mode. The number of possible target shapes across trials is indicated by “# shapes”. The nontargets in a given trial could either be the same or there could be other unique elements (“various”). Target and nontargets switched roles randomly in mixed-feature search. See the introduction for more detailed explanations and References.

Title	Target (# shapes)	NonTargets	Roles	Interference	ERP
mixed-feature search	singleton (2)	same	swaps	large	mostly N2pc
fixed-feature search	singleton (1)	same	fixed	intermediate	P_D
singleton detection	singleton (3)	same	fixed	intermediate	P_D
feature search	non-singleton (1)	various	fixed	absent	none

2. Experiment 1

As outlined above, the electrophysiological correlates of fixed- and mixed-feature search in the additional singleton are well-studied. However, electrophysiological investigations of singleton detection and feature search modes are missing. Therefore, little is known about the mechanism that prevents salient-but-irrelevant color singletons from disrupting visual search in feature search mode (e.g., Bacon & Egeth, 1994; Kerzel & Barras, 2015; Leber & Egeth, 2006; Zehetleitner, Goschy, & Müller, 2012). In general, there are two ways in which resistance to interference in feature search mode may be implemented. The task-relevant features may be enhanced (e.g., Folk et al., 1992; Wolfe, 1994) or distracting signals may be inhibited (e.g., Gaspar & McDonald, 2014; Moher, Abrams, Egeth, Yantis, & Stuphorn, 2011; Zehetleitner et al., 2012). While enhancement of target features should be reflected in changes of the N2pc to the target, suppression of distracting features should be reflected in changes of the P_D to the distractor. Under the assumption that more efficient rejection of distractors in feature search was accomplished by stronger suppression, we predict a stronger P_D in feature search than in singleton detection mode. In any case, we do not expect an N2pc to the color distractor in either search mode because nontarget and target shapes did not swap roles.

We modeled our stimuli on a previous study by Leber and Egeth (2006). In singleton detection mode, the target shape varied unpredictably between a triangle, a diamond, and a circle while the nontargets were always squares. In feature search mode, the target shape was a circle and two of the nontarget squares were replaced by other unique shapes (i.e., a triangle and a diamond, see Fig. 1). While it is generally undesirable to use distinct displays in ERP experiments, we minimized differences in luminance between the various shapes by adjusting the number of pixels composing each shape. As a matter of fact, the number of pixels was identical for each shape and the overall luminance was thus perfectly balanced. However, it is still possible that neural activity varies as a function of shape. For instance, a triangle has more intersections than a circle but fewer than a rectangle and the neural response of cells in visual cortex sensitive to intersections may therefore differ. There is no way of controlling for this problem, but we believe that the random placement of shapes will cancel out these effects.

To measure lateralized ERPs to distractors, we were particularly interested in the spatial configuration where the target was on the vertical midline and the distractor was on the left or right (see column 5 in Fig. 1). However, to make the displays unpredictable, target and distractor were randomly positioned according to the spatial configurations illustrated in Fig. 1. We will present detailed analyses of the configurations with ipsi- and contralateral distractors (see columns 3 and 4) where the electrophysiological response to the target and the electrophysiological response to the distractor may partially cancel or add up (Gaspar & McDonald, 2014). More precisely, the expected contralateral positivity to the distractor and the expected contralateral negativity to the target will add up when target and distractor are placed on opposite sides, but will partially cancel when they are placed on the same side. Further, spatial configurations featuring a lateral target without distractor or a lateral target with a midline distractor (see columns 1 and 2) are less interesting for our present purpose, but provide useful baseline conditions.

As an index of the early saliency signal, we also evaluated lateralized ERPs before the N2pc time interval. A posterior positivity between 140 and 190 ms (Fortier-Gauthier, Moffat, Dell'Acqua, McDonald, & Jolicœur, 2012; Gokce, Geyer, Finke, Mueller, & Töllner, 2014; Jannati et al., 2013) has been labeled Ppc and may reflect initial processing of the stimuli based on feature discontinuities, which may later guide attentional selection or suppression as indexed by the N2pc and P_D . After visual inspection of the data,

we focus on a slightly later interval around the peak of the N1 from 160 to 210 ms, but we believe that the same underlying process is captured.

2.1. Methods

2.1.1. Participants

Forty-two first-year psychology students from the University of Geneva participated for class credit. Thirty-two were retained in the final sample, 17 in the singleton and 15 in the feature group. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed consent was given before the experiment started.

2.1.2. Apparatus and stimuli

Stimuli were displayed on a 22 inch flat-panel monitor with a refresh rate of 60 Hz and a pixel resolution of 1920×1080 (horizontal \times vertical) that was viewed at a distance of 80 cm. The background was black and the stimuli were either red or green. The colors had the same physical luminance of 15.6 cd/m^2 . A white fixation cross was presented in the center of the screen. The search array was presented on a virtual circle with an eccentricity of 3.5° . The search array consisted of 8 equally spaced items, with two items on the vertical midline. The outline shapes were a circle (diameter 1.5°), a square (side length 1.1°), a diamond (square rotated by 90°) or a triangle (side length 1.7°). Stroke width and size were slightly adjusted to give exactly the same number of colored pixels (696) for each shape. A vertical or horizontal gray line of 0.75° length and 15.6 cd/m^2 luminance was presented in the center of each shape. Stroke width was approximately 0.06° for all items.

2.1.3. Electrophysiological recording and analysis

An actiChamp amplifier (Brain Products, Gilching, Germany) with active Ag/AgCl electrodes sampled at 1000 Hz was used. We fixed 26 electrodes on the scalp, one on the outer canthi of each eye (HEOG), one above and one below the right eye (VEOG), and one on each earlobe. Cz served as online reference and Afz as ground.

Offline, the data were band-pass filtered with cutoffs of 0.1 and 40 Hz and re-referenced to the average earlobes. Epochs extended from 100 ms before to 400 ms after stimulus onset and the interval from 100 ms before to stimulus onset was used for baseline correction. We excluded blinks and vertical eye movements (difference in VEOG channels or Fp1/Fp2 exceeding $\pm 60 \mu\text{V}$), horizontal eye movements (difference in HEOG channels exceeding $\pm 30 \mu\text{V}$), and muscular artifacts (any electrode exceeding $\pm 80 \mu\text{V}$). We computed the average difference in the HEOG channels for left and right stimuli separately. Then, we rejected 9 participants with voltages exceeding $3 \mu\text{V}$ in the difference traces until 300 ms after stimulus onset. This was done to ensure that no systematic eye-movements over 0.2° were included in the data (Lins, Picton, Berg, & Scherg, 1993). One further participant was removed because of less than 60 valid trials in at least one of the conditions.

2.1.4. Between-subject variable

Participants in singleton detection mode searched for a unique shape (diamond, circle, or triangle) among nontargets that were of identical shape (seven squares). Each unique shape occurred randomly in one third of the trials. Participants in feature search mode searched for the same shape (circle) that occurred among heterogeneous distractors. In addition to the circle, there were always one diamond, one triangle and five squares.

2.1.5. Within-subject variables

Following Gaspar and McDonald (2014), target and distractor locations were varied to produce the following configurations (see Fig. 1): lateral target, no distractor (33% of trials), midline target, no distractor (17%), lateral target, midline distractor (11%), lateral target, ipsilateral distractor (11%), lateral target, contralateral distractor (11%), midline target, lateral distractor (11%), midline target, midline distractor (6%). Thus, distractor-present and distractor-absent trials were equally likely. In distractor absent trials, all outline shapes had the same color. In distractor present trials, one distractor element had a different color.

2.1.6. Procedure

Participants were asked to report the orientation of the line inside the target shape by pressing one of two keys. The arrow-left and arrow-right keys on a standard keyboard were used. Participants were asked to maintain fixation on the central fixation cross, ignore the colors, and respond as rapidly as possible while keeping the error rate below 10%. After blocks of 36 trials, the error rate was shown for 5 s, forcing participants to take a short break. Due to an error, the first 14 participants completed 1152 trials and the following subjects completed 1296 trials. The color of target and distractor were swapped after half of the experimental trials to cancel out possible inequalities between the two colors. Before the swap, some practice trials were presented to familiarize participants with the new color assignment.

Participants in singleton detection mode were asked to search for the item with a unique shape, whereas participants in feature search mode were asked to search for the circle. At the beginning of the experiment, participants practiced the experimental task until they felt comfortable with it. Practice trials were not recorded, but participants completed at least 30 trials. A trial started with the presentation of the fixation cross for a randomly selected duration between 0.5 and 1 s. Then, the search display appeared and stayed on the screen until a response was registered. The following response errors were reported to the participant by visual feedback: choice errors, anticipations (RTs < 0.2 s), and late trials (RTs > 2 s).

2.2. Behavioral results

Only conditions with a lateral target or lateral distractor were analyzed (78% of all trials) because only these trials could be used in the analysis of lateralized ERPs. Trials not meeting the online criterion of 2 s (0.3%) and the rare anticipations (less than 0.01%) were excluded from analysis. Subsequently, data were trimmed for each participant and condition by removing trials slower than 2.5 times the standard deviation of the respective condition mean. This resulted in the exclusion of 3.1% of the trials.

2.2.1. RTs

Mean individual RTs were entered into a mixed-factors 2 (search mode: singleton, feature) \times 2 (distractor: presence, absence) ANOVA. As shown in the left panel of Fig. 2, There was a tendency for shorter RTs in feature search than in singleton detection mode (673 vs. 713 ms), $F(1,30)=2.9$, $p=0.099$, $\eta_p^2=0.088$. RTs were shorter in distractor-absent than distractor-present trials (685 vs. 701 ms), $F(1,30)=46.71$, $p<0.001$, $\eta_p^2=0.609$. The distractor effect was modulated by search mode, $F(1,30)=26.34$, $p<0.001$, $\eta_p^2=0.468$, showing that the distractor effect was larger in singleton detection (698 vs. 728 ms) than in feature search mode (671 vs. 675 ms). Follow-up *t*-tests showed that the distractor effect was significant in singleton detection (30 ms), $t(16)=6.85$, $p<0.001$, and in feature search mode (4 ms), $t(14)=2.19$, $p=0.046$.

Interference from the distractor is stronger when target and distractor are close than when they are far apart (Gaspar and McDonald, 2014; Mounts, 2000; Mathot, Hickey, & Theeuwes,

2010). To evaluate effects of distance, we ran a 2 (search mode: singleton detection, feature search) \times 4 (distance: 1, 2, 3, or 4 items) mixed-factors ANOVA on RTs from the distractor-present condition. We observed shorter RTs in feature search than in singleton detection mode, $F(1,30)=4.89$, $p=0.035$, $\eta_p^2=0.14$, and shorter RTs with increasing distance, $F(3,90)=24.13$, $p<0.001$, $\eta_p^2=0.446$. The interaction, $F(3,90)=7.59$, $p<0.001$, $\eta_p^2=0.202$, showed that the effect of distance was larger in singleton detection than in feature search mode. Separate one-way ANOVAs for each group showed that RTs decreased with increasing distance in singleton detection mode (757, 729, 712, and 711 ms), $F(3,48)=22.42$, $p<0.001$, $\eta_p^2=0.584$, and also in feature search mode (682, 675, 672, and 666 ms), $F(3,42)=4.58$, $p=0.007$, $\eta_p^2=0.246$.

2.2.2. Choice errors

The same ANOVA as above was run on mean percentage of choice errors. Errors were less frequent when the distractor was absent than when it was present (4.8% vs. 5.5%), $F(1,30)=8.30$, $p=0.007$, $\eta_p^2=0.217$. The interaction, $F(1,30)=5.18$, $p=0.03$, $\eta_p^2=0.147$, showed that the distractor effect was larger in singleton detection (5.6% vs. 6.9%) than in feature search mode (4.0% vs. 4.1%).

2.3. Electrophysiological results

The ipsi- and contralateral potentials at electrodes PO7/PO8 as well as the difference waves are shown in Fig. 3. Note that ipsi- and contralateral was determined with respect to lateral targets with the exception of the last column of Fig. 3, where ipsi- and contralateral was determined with respect to the lateral distractor.

2.3.1. Overview of results

Importantly, a positive difference emerged to the lateral distractor with midline target in the N2-interval (see column 5 in Fig. 3), which corresponds to the P_D component. While the P_D occurred in singleton detection mode, it was absent in feature search mode. Inspection of columns 1–4 in Fig. 3 shows that a robust N2pc occurred to lateral targets. Before, a positivity to the distractor occurred in the N1-interval that we relate to the P_{pc} . The positivity occurred to distractors ipsilateral to the target (see column 3) and to lateral distractors with midline targets (see column 5). With contralateral distractors (see column 4), the positive difference turned into a negative difference because ipsi- and contralateral were inverted with respect to the distractor. Note that the target was always used as reference.

2.3.2. Selection of averaging windows

The difference between ipsi- and contralateral voltages at electrodes PO7/PO8 in the N1- and N2-intervals were analyzed by calculating the means in 50 ms time intervals (see bottom row in Fig. 3). As visible in the difference waves, clear peaks in the N1-interval were absent. We therefore first calculated the moving average (50 ms width) of the grand-average waveform and fixed the N1-averaging interval to a 50 ms window around the peak of the N1, from 163 to 213 ms. In the N2-interval, peaks were clearly visible in the difference waves when there was a lateral target. However, visual inspection suggests that components in the N1-interval overlapped with components in the N2-interval and latencies were not equal. Therefore, we did not use fixed averaging windows, but focused on the peaks. To place the averaging intervals on the peak of each individual condition, we first calculated the moving average (50 ms width) over the difference waveform of each condition. Then, the time window was placed on the local minimum in the interval from 200 to 350 ms for the N2pc. This resulted in slightly different averaging windows that started between 246 and 267 ms (mean 256 ms), depending on the condition. For the

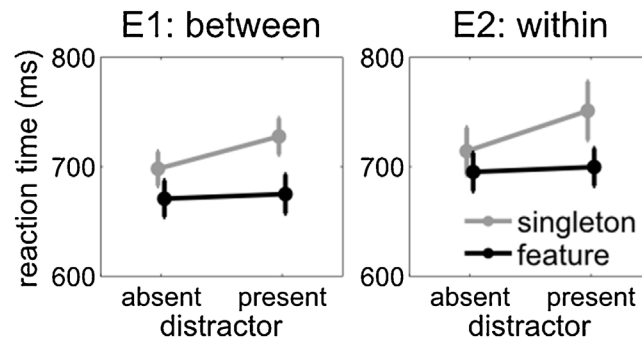


Fig. 2. Behavioral results from Experiments 1 and 2. Mean reaction times are shown as a function of distractor presence, search mode, and experiment. Experiments 1 and 2 were run between- and within-subjects, respectively.

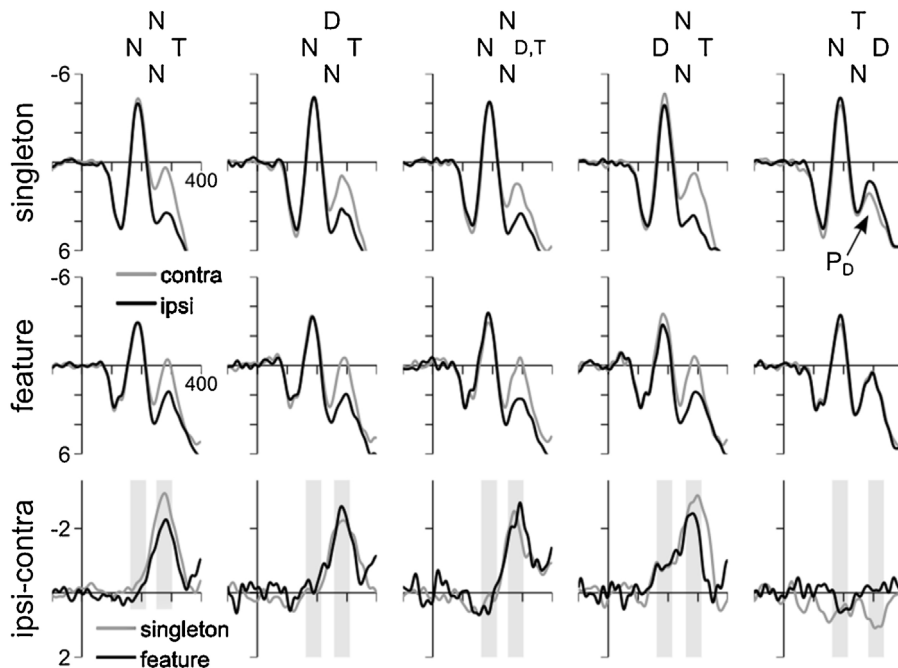


Fig. 3. Electrophysiological results from Experiment 1 where a between-subjects design was used. Microvolts are plotted on the y-axes and milliseconds on the x-axes. Rows 1 and 2 show the contra- and ipsilateral waveforms from the singleton detection and feature search groups, respectively. Row 3 shows the difference between contra- and ipsilateral waveforms for the singleton detection and feature search groups. Insets show the schematic target (T), distractor (D), and nontarget (N) positions. The gray rectangles show the mean averaging windows.

lateral distractor/midline target condition in singleton detection mode (see column 5 in Fig. 3), we used the same procedure to look for a maximum because visual inspection suggests that the polarity changed in this condition. The averaging window was set from 287 to 337 ms, which corresponds to the peak of the N2. Because there was no peak in the corresponding condition in feature search mode, we applied the averaging window from singleton detection mode. The mean voltages for the two intervals of interest are presented in Fig. 4.

Before running the analyses, we removed 13.6% of the data based on the electrophysiological criteria enumerated above. After trial rejection based on online behavioral and offline electrophysiological criteria, 84.4% of the trials remained for analysis.

2.3.3. N1-interval

We conducted a mixed-factor 2 (search mode: singleton, feature) \times 5 (stimulus configuration: see above) ANOVA on the mean voltage difference between contra- and ipsilateral in the interval from 163 to 213 ms. The ANOVA showed that stimulus configuration had an effect, $F(4,120)=16.99$, $p<0.001$, $\eta_p^2=0.362$, but

neither the effect of search mode, $p=0.830$, nor the interaction, $p=0.543$, reached significance. Inspection of the upper left panel in Fig. 4 shows that the effect of configuration was mainly due to positive differences with ipsilateral distractor ($0.27 \mu V$) and lateral distractor/midline target ($0.37 \mu V$). In contrast, the contralateral distractor produced a negative difference ($-0.82 \mu V$). These findings are consistent with a contralateral positivity in response to the color distractor occurring in the N1 interval, similar to the Ppc. When the distractor was shown on the same side as the target, the positivity is expressed as a negative difference for technical reasons. Importantly, the pattern of results was similar for both search modes. *T*-tests comparing the means for each configuration to zero are presented in Table 2.

2.3.4. N2-interval

The same mixed-factor ANOVA as above revealed an effect of stimulus configuration, $F(4,120)=56.33$, $p<0.001$, $\eta_p^2=0.655$, showing that the voltage difference changed from about $-2.4 \mu V$ in the four configurations with lateral target to $0.4 \mu V$ in the condition with midline target and lateral distractor (see lower left panel

Table 2

Mean voltages in microvolt (μV) for each spatial configuration in the N1-interval, collapsed across search modes, and results of a t -test against zero. The sample size was 32 in Experiment 1 (collapsed across groups) and 12 in Experiment 2.

position		Experiment 1		Experiment 2			
target	distractor	μV	t-value	p-value	μV	t-value	p-value
lateral	–	–0.19	–2.62	0.014	–0.15	–1.31	0.217
lateral	midline	–0.16	–1.38	0.167	–0.36	–3.33	0.007
lateral	ipsi	0.27	2.04	0.050	0.41	3.23	0.008
lateral	contra	–0.82	–6.15	<0.001	–0.55	–5.37	<0.001
midline	lateral	0.47	4.07	<0.001	0.51	2.72	0.020

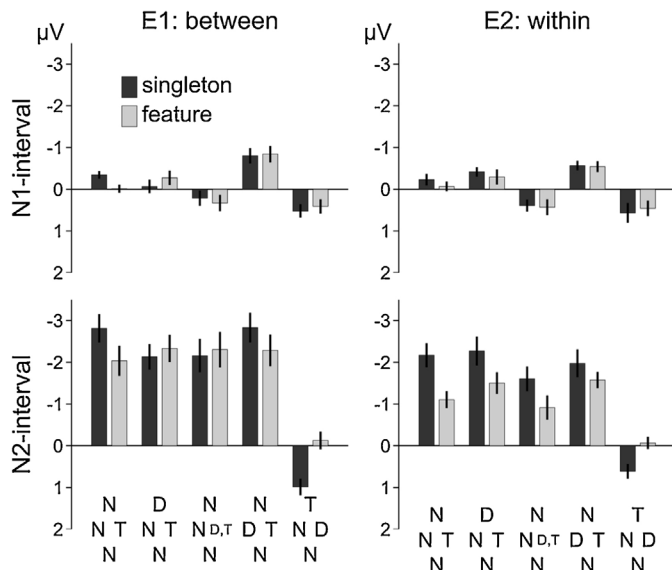


Fig. 4. The mean voltage difference between contra- and ipsilateral electrodes in the N1-interval (163–213 ms, see row 1) and the N2pc-interval (about 250–300 ms, see row 2) as a function of stimulus configuration and search mode in Experiments 1 and 2 (left and right columns, respectively). Error bars show the between-subject standard error of the mean. Insets show the schematic target (T), distractor (D), and nontarget (N) positions.

in Fig. 4). The effect of stimulus configuration was modulated by search mode, $F(4,120)=4.96$, $p=0.001$, $\eta_p^2=0.142$, showing that there was a significant positive difference with lateral distractor/midline target in singleton detection mode ($1 \mu\text{V}$), $t(16)=5.56$, $p<0.001$, that was absent in feature search mode ($-0.13 \mu\text{V}$), $p=0.569$. An independent-samples t -test confirmed the difference between singleton detection and feature search mode, $t(30)=3.83$, $p=0.001$. In contrast, the remaining spatial configurations did not differ as a function of search mode, $ps>0.12$. Thus, a P_D to the distractor occurred in singleton detection mode and no lateralized ERP was found in feature search mode. Further, as visible in Fig. 4, the N2pc was significantly different from zero in all configurations with lateral target, $ts>4.8$, $ps<0.001$.

Previous research has demonstrated that the P_D to the distractor and the N2pc to the target (more precisely: the N_T) add up or partially cancel (Gaspar & McDonald, 2014). We carried out a separate 2 (search mode: singleton, feature) \times 2 (configuration: ipsilateral distractor, contralateral distractor) ANOVA and expected a larger N2pc to the lateral target with contralateral than with ipsilateral distractors. The main effect of configuration failed to reach significance ($-2.6 \mu\text{V}$ vs. $-2.2 \mu\text{V}$ for contra- and ipsilateral), $F(1,30)=2.83$, $p=0.103$, $\eta_p^2=0.086$. The interaction between search mode and configuration approached significance, $F(1,30)=3.15$, $p=0.086$, $\eta_p^2=0.095$, showing that the N2pc to the target was larger with contra- than with ipsilateral distractors in singleton detection (-2.8 vs. $-2.2 \mu\text{V}$), but not in feature search mode (-2.3 vs. $-2.3 \mu\text{V}$). The interaction is consistent with the fact

that there was a P_D to the lateral distractor (with midline target) in singleton detection, but not in feature search mode. Therefore, a difference between contra- and ipsilateral distractors was only expected for singleton detection mode.

2.4. Discussion

We measured RTs and lateralized ERPs in singleton detection and feature search modes in different groups of observers. Consistent with the previous literature (Bacon & Egeth, 1994; Leber & Egeth, 2006), there was an increase in RT with a salient-but-irrelevant color singleton in singleton detection mode, but this increase was close to absent in feature search mode, suggesting that distractor rejection was complete in feature search mode. Further, interference decreased with increasing distance between target and distractor in singleton detection and feature search modes. The main finding from the ERP recordings was that there was a P_D to the distractor in singleton detection, but not in feature search mode, suggesting that resistance to interference in feature mode was not based on active suppression. Further, we observed an early positivity to the distractor in the N1-interval that was independent of search mode. We consider the positive difference as the Ppc-component, which is believed to reflect imbalanced saliency (Fortier-Gauthier et al., 2012).

3. Experiment 2

The principal aim of Experiment 2 was to confirm the results from Experiment 1 in a within-subject design.

3.1. Methods

The methods were as in Experiment 1 with the following exceptions. The singleton and feature search conditions were administered to the same group of participants in two separate sessions. In each session, singleton detection and feature search alternated in four blocks of 288 trials. Colors were swapped after two blocks. Each block was preceded by a few practice trials that were not recorded. A total of 2304 trials was recorded per participants. Sixteen students participated, but only 12 remained in the final sample. Two were removed because of deviations in the EOG-difference waves exceeding $3 \mu\text{V}$ until 300 ms after stimulus offset, and two further participants only completed one session.

3.2. Behavioral results

Trials not meeting the online criterion of 2 s (0.4%), the rare anticipations (less than 0.01%) and outliers (3.2%) were excluded from analysis.

3.2.1. RTs

Mean individual RTs were entered into a within-subjects 2 (search mode: singleton detection, feature search) \times 2 (distractor: presence, absence) ANOVA. As shown in Fig. 2, RTs were shorter in

feature search than in singleton detection mode (690 vs. 726 ms), $F(1,11)=9.13$, $p=0.012$, $\eta_p^2=0.454$, and in distractor-absent than distractor-present trials (698 vs. 718 ms), $F(1,11)=30.84$, $p<0.001$, $\eta_p^2=0.737$. The distractor effect was modulated by search mode, $F(1,11)=16.89$, $p=0.002$, $\eta_p^2=0.606$, showing that the distractor effect was larger in singleton detection (707 vs. 744 ms) than in feature search mode (688 vs. 692 ms). Follow-up t -tests showed that the distractor effect was significant in singleton detection mode (37 ms), $t(11)=5.25$, $p<0.001$, but not in feature search mode (5 ms), $t(11)=1.46$, $p=0.172$.

To evaluate effects of target-distractor distance, we ran a 2 (search mode: singleton detection, feature search) \times 4 (distance: 1, 2, 3, or 4 items) within-subjects ANOVA on RTs from the distractor-present condition. We observed shorter RTs in feature search than in singleton detection mode, $F(1,11)=11.3$, $p=0.006$, $\eta_p^2=0.507$, and shorter RTs with increasing distance (739, 726, 717, and 715 ms), $F(3,33)=9.16$, $p<0.001$, $\eta_p^2=0.454$. The interaction was not significant, $p=0.352$, suggesting that the effect of distance did not differ between singleton detection and feature search modes.

3.2.2. Choice errors

The same ANOVA as above was run on mean percentage of choice errors. Errors tended to be less frequent when the distractor was absent than when it was present (3.8% vs. 4.3%), $F(1,11)=3.88$, $p=0.074$, $\eta_p^2=0.261$. The interaction was not significant, $p=0.489$.

3.3. Electrophysiological results

3.3.1. Overview of results

The ipsi- and contralateral potentials at electrodes PO7/PO8 as well as the difference waves are shown in Fig. 5. Comparison of Figs. 3 and 5 suggests that results were similar in the between- and within-subjects designs with one remarkable exception. In the within-subject design of the present experiment, the N2pc to the target (columns 1–4 of Fig. 5) was larger in singleton detection than in feature search mode. This difference did not reach significance in the between-subjects design of Experiment 1. Otherwise, the results are very similar. Most important, there was a P_D in the N2-interval in singleton detection mode that was not present in feature search mode (see column 5). Further, there was a positivity to the distractor in the N1-interval with ipsilateral distractor and lateral distractor/midline target (see columns 3 and 5) that turned into a negative difference with contralateral distractors (see column 4) for technical reasons.

3.3.2. Calculation of averaging windows

The analyses windows of 50 ms width were determined as in Experiment 1. The window for the N1 started at 163 ms. The window for the N2pc started between 238 and 256 ms with a mean of 250 ms and the window for the P_D started at 256 ms. Before running the analyses, we removed 11.4% of the data based on the electrophysiological criteria enumerated above. After trial rejection based on online behavioral and offline electrophysiological criteria, 85.2% of the trials remained for analysis.

3.3.3. N1-interval

We conducted a within-subjects 2 (search mode: singleton, feature) \times 5 (stimulus configuration: see above) ANOVA on the mean voltage difference between contra- and ipsilateral in the interval from 163 to 213 ms (see upper right panel of Fig. 4). The ANOVA showed that stimulus configuration had an effect, $F(4,44)=19.44$, $p<0.001$, $\eta_p^2=0.639$, but neither the effect of search mode, $p=0.530$, nor the interaction, $p=0.868$, reached significance. Inspection of the upper right panel in Fig. 3 shows that the main effect of configuration was mainly due to positive differences with ipsilateral distractor (0.41 μ V) and lateral distractor/midline

target (0.51 μ V) conditions. In contrast, the contralateral distractor produced a negative difference (−0.55 μ V). These findings are consistent with a contralateral positivity in response to the color distractor occurring in the N1-interval, similar to the Ppc. Importantly, the pattern of results did not change as a function of search mode. t -tests comparing the means for each configuration to zero are presented in Table 2.

3.3.4. N2-interval

The same mixed-factor ANOVA as above revealed an effect of stimulus configuration, $F(4,44)=29.83$, $p<0.001$, $\eta_p^2=0.731$, showing that the voltage difference changed from about −1.6 μ V in the four configurations with lateral target to 0.2 μ V in the condition with midline target and lateral distractor (see lower right panel in Fig. 4). The voltage difference was larger in singleton detection than in feature search mode (−1.5 vs. −1.0 μ V), $F(1,11)=6.82$, $p=0.024$, $\eta_p^2=0.383$. The interaction of stimulus configuration and search mode was significant, $F(4,44)=10.64$, $p<0.001$, $\eta_p^2=0.492$, showing that there was a significant positive difference with lateral distractor/midline target in singleton detection mode (0.6 μ V), $t(11)=3.46$, $p=0.005$, that was absent in feature search mode (−0.1 μ V), $p=0.66$. A t -test confirmed the difference between singleton detection and feature search modes, $t(11)=3.90$, $p=0.002$. Thus, a P_D to the distractor occurred in singleton detection mode and no lateralized ERP was found in feature search mode, which replicates the results of Experiment 1.

Next, we subjected the four configurations with a lateral target to a 2 (search mode: singleton, feature) \times 4 (stimulus configuration) ANOVA to separately investigate the N2pc to the lateral target. The ANOVA returned a main effect of search mode, $F(1,11)=11.28$, $p=0.006$, $\eta_p^2=0.506$, showing that the N2pc to the target was indeed larger in singleton detection than in feature search mode (−2.0 vs. −1.3 μ V). The main effect of spatial configuration, $F(3,33)=3.90$, $p=0.017$, $\eta_p^2=0.262$, showed that the N2pc was smaller with ipsilateral distractors (−1.3 μ V) than with lateral targets alone (−1.6 μ V), midline (−1.9 μ V), and contralateral distractors (−1.8 μ V).

To further test the idea that the P_D to the distractor and the N2pc to the target add up or partially cancel (Gaspar & McDonald, 2014), we carried out a separate 2 (search mode: singleton, feature) \times 2 (configuration: ipsilateral distractor, contralateral distractor) ANOVA and expected a larger N2pc to lateral targets with contralateral than with ipsilateral distractors. The main effect of search mode was confirmed, $F(1,11)=6.13$, $p=0.031$, $\eta_p^2=0.358$, and the main effect of configuration approached significance, $F(1,11)=4.58$, $p=0.056$, $\eta_p^2=0.294$, showing a more negative N2pc to lateral targets with contralateral than ipsilateral distractors (−1.8 vs. −1.3 μ V), which is consistent with the proposition. However, the interaction was not significant, $p=0.407$.

3.4. Discussion

We replicated the most important result from Experiment 1: There was a P_D to the color distractor in singleton detection mode, but no lateralized ERP occurred in the N2-interval in feature search mode. Thus, there is evidence of suppression of salient-but-irrelevant stimuli when observers search for singletons, but not when they search for a particular feature. Again, there was an early positivity to the distractor in the N1-interval that was independent of search mode. The early positivity may correspond to the Ppc-component. Also, there was some evidence that the P_D to the distractor and the N2pc to the target combine.

However, there was one important difference between the between-subject and within-subject design. In the present experiment, we observed a reduced N2pc to the target in feature search mode than in singleton detection mode. In contrast, there was no

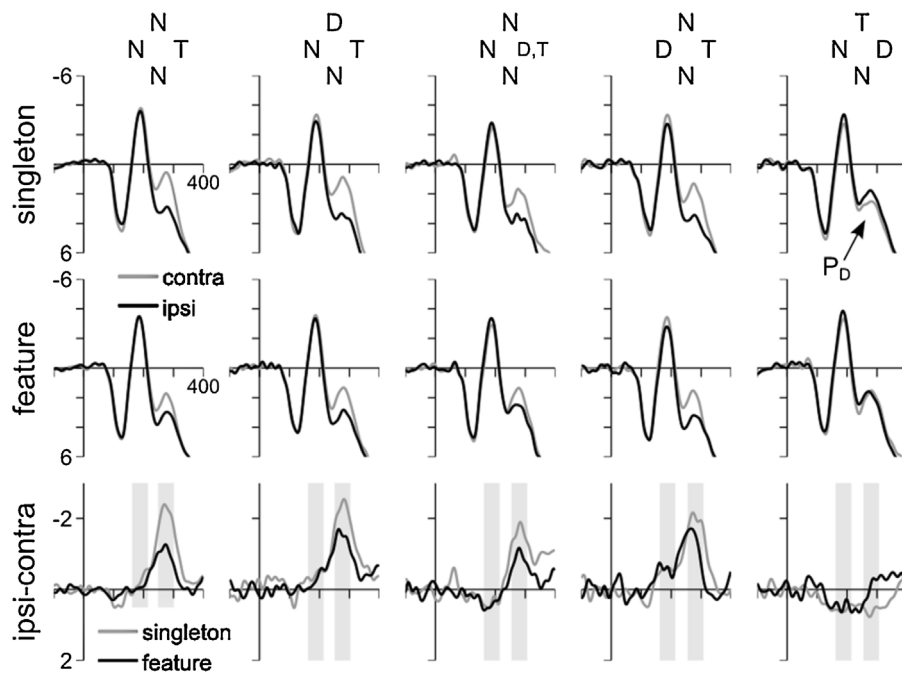


Fig. 5. Electrophysiological results from Experiment 2 where a within-subjects design was used. Microvolts are plotted on the y-axes and milliseconds on the x-axes. Rows 1 and 2 show the contra- and ipsilateral waveforms from the singleton detection and feature search modes, respectively. Row 3 shows the difference between contra- and ipsilateral waveforms for singleton detection and feature search modes. Insets show the schematic target (T), distractor (D), and nontarget (N) positions. The gray rectangles show the mean averaging windows.

effect of search mode on the N2pc to the target in Experiment 1. Possibly, we did not have enough power to detect such a difference in the between-subjects design. The change in N2pc-amplitude may be related to task requirements. Luck, Girelli, McDermott, and Ford (1997) found a reduced N2pc with an easier feature detection task than with a more difficult orientation discrimination task, suggesting that the N2pc-amplitude reflects the difficulty of the search task. Thus, somewhat surprisingly, the larger N2pc in singleton detection mode shows that saliency-driven search was less efficient than search for a non-salient, but fixed feature. To support this conclusion, we compared RTs in the distractor-absent condition. RTs were 19 ms shorter in feature search than in singleton detection mode (688 vs. 707 ms), $t(11) = 2.18$, $p = 0.052$, confirming that feature search was more efficient.¹

4. General discussion

We observed a P_D to the distractor in singleton detection mode and no lateralized ERP in feature search mode. We conclude that distractor suppression, as indexed by the P_D , is associated with RT interference in singleton detection mode. In feature search mode, there was no behavioral interference from the color distractor and the P_D was absent. Thus, our main finding is that conditions which avoid interference from salient-but-irrelevant distractors show no electrophysiological evidence for suppression, whereas conditions with interference may be accompanied by a P_D .

Regarding the mechanism that prevents salient-but-irrelevant distractors from disrupting visual search in feature search mode, the current results favor the view that resistance to interference is implemented by enhancement of the target feature (e.g., Folk et al., 1992; Wolfe, 1994) rather than by distractor suppression (e.g., Gaspar & McDonald, 2014; Moher et al., 2011; Zehetleitner et al.,

2012). The reduced target-related N2pc in feature search mode in Experiment 2 suggests that it was easier to locate the target in feature search than in singleton detection mode, which we ascribe to enhancement of the target features.

We find that alternative explanations of the reduced N2pc in feature search are less likely. For instance, one may argue that inter-trial priming explains the advantage of feature search over singleton detection mode (see Lamy, Carmel, Egeth, & Leber, 2006; Leonard & Egeth, 2008). In feature search mode, the target feature is repeatedly selected, which facilitates search (review in Lamy & Kristjánsson, 2013), whereas the target feature does not repeat as often in singleton detection mode. However, inter-trial priming cannot entirely account for resistance to interference in feature search mode because the target feature also repeats in the fixed-feature version of the additional singleton paradigm, where robust behavioral interference and a P_D to the distractor has been observed (Burra & Kerzel, 2013; Jannati et al., 2013). Rather, we think that the task requirements in feature search result in enhancement of the target feature that is reflected in the reduced N2pc to the target. A similar conclusion has been reached in research on the modified spatial cueing paradigm, where irrelevant cues can be entirely ignored in favor of task-relevant stimuli (Folk et al., 1992; Lien, Ruthruff, Goodin, & Remington, 2008).

Further, the absence of the P_D in feature search mode and its presence in singleton detection mode suggests that distractor suppression is an effortful process that incurs a delay. Previously, it was noted that the P_D to the distractor was present in trials with short RTs, suggesting that suppression helped participants locate the target (Gaspar & McDonald, 2014; Jannati et al., 2013; McDonald et al., 2013). Therefore, one may have suspected the P_D to occur in feature search mode where distractor rejection was successful. However, the present findings suggest that the P_D only occurs when distractor processing was initiated. In this case, active suppression may be necessary to guide attention away from the salient-but-irrelevant stimuli. Thus, the elimination of distractor interference in feature search mode is achieved by a top-down set that prevents further

¹ When the two excluded subjects were replaced in the sample, this difference reached significance (19 ms), $t(13) = 2.27$, $p = 0.04$.

processing of the distractor altogether, presumably by enhancing the top-down set for the target feature.

The present results extend the signal-suppression hypothesis (Sawaki, Geng, & Luck, 2012; Sawaki & Luck, 2010, 2012) in important ways. According to this hypothesis, salient stimuli generate an attend-to-me signal that is suppressed if it does not match the top-down task set. The results in singleton detection mode are fully consistent with the suppression hypothesis: There was a Ppc to the salient-but-irrelevant stimulus, reflecting the attend-to-me signal, followed by a P_D, reflecting suppression. However, the same color singleton produced an attend-to-me signal, but no suppression when participants performed feature search. Thus, a top-down set that is strong enough to prevent behavioral signs of attentional capture averts further processing of the attend-to-me signal and makes suppression unnecessary.

4.1. Summation of P_D and N2pc (N_T)

The N2pc component has been associated with two distinct functions serving target identification. Luck and Hillyard (1994) proposed that the N2pc reflected the suppression of competing information from surrounding distractors, whereas Eimer (1996) suggested that it reflected selection of target features. Some recent studies did not provide evidence for the role of distractor suppression in the N2pc (Mazza, Turatto, & Caramazza, 2009a, 2009b), but this issue is far from settled. Hickey et al. (2009) suggested that the N2pc was composed of a negativity arising contralateral to the attended target, the N_T, reflecting target processing, and a positivity arising contralateral to the unattended distractor, the P_D, reflecting distractor suppression. When target and distractor are shown in opposite hemifields, the N_T and P_D add up to yield the N2pc. Gaspar and McDonald (2014) demonstrated the summation of P_D and N_T using displays with a color target and a differently colored distractor. The N2pc was measured in a configuration with lateral target and contralateral distractor, which combines target and distractor processing. The size of the N2pc corresponded to the sum of the N_T, measured in response to a lateral target only, and the P_D, measured in response to a lateral distractor only. In the present study, we found some evidence in the amplitude of the N2pc that supports the summation hypothesis. Notably, the N2pc tended to be larger with contralateral than ipsilateral distractors. With contralateral distractors, the contralateral positivity to the distractor and the contralateral negativity to the target would add up, while they partially cancel with ipsilateral distractors.

However, the summation hypothesis predicts a difference between contra- and ipsilateral configurations only when there was a P_D to the distractor. In feature search, the distractor-related P_D was absent, but there was only weak statistical support for the reduction of the difference between ipsi- and contralateral distractors in this condition. That is, the interaction of search mode and configuration (contra-, ipsilateral) approached significance in Experiment 1, but was not significant in Experiment 2. Possibly, the summation of the distractor-related P_D and the target-related N2pc was masked by the slightly different onsets of the two components, which made this difference unreliable in our data set.

4.2. Effects of target-distractor distance

We observed that interference was stronger with close than with far distractors irrespective of search mode. Previous studies chalked up the stronger interference with close distractors to stronger competition between stimuli that are in the same receptive field (Gaspar & McDonald, 2014; Mathot et al., 2010; Mounts, 2000). Mounts (2000) suggested that the target initially loses the competition with the salient distractor. Because competition is stronger with small target-distractor separations than

with large separations, behavioral interference is also greater. Surprisingly, the distance effect in our study persisted in feature search mode where behavioral interference was absent. The RTs in the distractor-present condition hovered around the mean of the distractor-absent condition, from +11 to –5 ms in the between-subject design and from +17 to –10 ms in the within-subject design. Thus, it appears that competition between target and distractors not only disrupts target processing at small distances, but also tends to facilitate selection at great distances when observers are in feature search mode. In any case, the distance effect was independent of distractor suppression, as the P_D was absent in feature search mode while the distance effect persisted.

4.3. The Ppc component

A posterior contralateral positivity in the 100–200 ms time range has been noted in previous studies in which a salient color singleton was shown on a lateral position (Fortier-Gauthier et al., 2012; Gokce et al., 2014; Jannati et al., 2013; Leblanc, Prime, & Jolicoeur, 2008; Sawaki & Luck, 2010). It was referred to as Ppc by Fortier-Gauthier et al. (2012) and P_D by Sawaki and Luck (2010). We decided to refer to it as Ppc to avoid confusion with the P_D in the N2 time range. As the colors were isoluminant and counter-balanced for each participant, the Ppc cannot reflect imbalanced luminance. Fortier-Gauthier et al. (2012) suggested that the Ppc may reflect initial processing of the stimuli based on feature discontinuities. However, the present results show that not all feature discontinuities result in a Ppc. While a colored stimulus evoked a Ppc when it was lateralized, a lateral shape singleton alone did not evoke a Ppc (see columns 1 and 2 in Figs. 3 and 5). It is likely that the Ppc is sensitive exclusively to color discontinuities because all previous reports of the Ppc involved color. On the other hand, it may also be possible that the shape discontinuity was not salient enough to produce a Ppc.

5. Summary

We measured ERPs to irrelevant-but-salient stimuli in singleton detection and feature search modes. Color distractors result in increased RTs in singleton detection mode, but not in feature search mode. We asked how resistance to interference is achieved and conjectured that distractor suppression, as indexed by the P_D, was involved. However, we did not observe a P_D to the distractor in feature search mode, but a reduced N2pc to the target. These results suggest that enhancement of target features prevents processing of the early attend-to-me signal (the Ppc) evoked by the color distractors. In contrast, there was a P_D to the distractor in singleton detection mode, suggesting that the P_D reflects a time-consuming process to abort the early attend-to-me signal. Overall, our results show that active distractor suppression does not underlie resistance to interference (in feature search mode), but occurs when distractors disrupt visual search (in singleton detection mode).

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