

## The allocation of attention in displays with simultaneously presented singletons

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### ABSTRACT

In an ERP experiment, we investigated whether a ‘permanent’ salient distractor changes the deployment of attention to target and nontarget singletons. Observers searched for a color target in a search array that mainly consisted of black vertical lines, but also always contained a line in a task-irrelevant color. Together with this distractor, a target or nontarget singleton was presented. Nontargets could be salient on the task-relevant dimension (color), or on a neutral dimension (line orientation). N2pc amplitude was maximal for targets, no N2pc was elicited by color nontargets, and orientation nontargets elicited an inverse N2pc. Targets and color nontargets elicited larger N2 amplitude than orientation singletons. P3 amplitude was high for relevant and low for irrelevant singletons. Targets also elicited higher reaction times and more errors. Attention seemed thus driven by the target feature, and by its feature dimension, even when constant distraction on that dimension had to be suppressed.

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### 1. Introduction

Attention is the cognitive mechanism that grants organisms the important ability to selectively process input from the environment. The deployment of attention across the visual field is a classic topic of study in experimental psychology. It is commonly studied by presenting observers with arrays of stimuli in which only a specified target stimulus is to be selected while others have to be ignored. The difficulty of this task can be manipulated in many ways, for instance by introducing distracting elements to the visual environment, or by presenting advance cues with certain validity. Such complications are thought to represent two key factors that affect the speed and success of attentional deployment. First, attention is dependent on the arrangement and properties of the visual scene. Second, the nature of the task the observer is trying to accomplish and the expectations that are consequently raised also affect attentional deployment. The first factor is often referred to as bottom-up or stimulus-driven control over attention, and the second factor is called top-down, or task-contingent control.

There is ample evidence to suggest that relatively low-level perceptual salience (e.g., unusually high luminance) is able to draw attention to a task-irrelevant stimulus (Theeuwes, 1991). However, it has also been shown that salient stimuli may be ignored

completely if they have no relevance for the task the observer is currently trying to do (Folk et al., 1992). Despite the appearance of a relatively large number of studies, the evidence accumulated to date has not provided completely decisive support for either view (Folk et al., 2002, 1994; Folk and Remington, 1998; Theeuwes, 1992, 1994; Theeuwes and Burger, 1998).

Recent studies have employed neurophysiological methods to observe the brain response more directly. The frequently used event-related potential (ERP) technique allows an assessment of neuronal activity with high temporal precision. Several ERP studies have used these methods to focus explicitly on the issue of bottom-up versus top-down control of attentional capture. The first of these to be discussed here was conducted by Girelli and Luck (1997). In their study, observers performed a singleton search task for color, orientation and motion targets. By measuring the N2 posterior-contralateral (N2pc) component of the ERP, the authors were able to track the deployment of attention across the visual field. The N2pc is a relatively early negative component that shows increased amplitude on posterior electrode sites that are contralateral to the visual hemifield in which a location or stimulus is attended, relative to ipsilateral sites. For example, if the observer attends to a stimulus in the left visual field, increased negative amplitude (in the N2 time range) would be recorded at right hemisphere electrode sites (e.g., PO8), relative to left hemisphere sites. The N2pc is interpreted as a reflection of attentional processing of, or shifting towards a target item at a lateral location in the visual field (Kiss et al., 2008a,b). The component is observed for lateralized target stimuli because of the contralateral organization of the visual system. Girelli and Luck (1997) showed that attention was not drawn to task-irrelevant

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color and orientation singletons, which confirmed earlier studies (Luck and Hillyard, 1994a,b). However, task-irrelevant motion singletons did attract attention, which suggested a stimulus-driven component to their processing. Evidence for stimulus-driven attentional capture by task-irrelevant color stimuli was provided by Hickey et al. (2006). In the critical condition of their second experiment, they asked observers to look for shape target stimuli in a circular search array, while simultaneously presenting a color distractor in the opposite hemifield. The N2pc component seemed to reflect an early tendency towards the salient but task-irrelevant distractor first, and only subsequently towards the actual target, which supported the idea that the component was affected by stimulus-driven attentional capture.

These findings have not gone undisputed, however. A series of studies by Eimer, Kiss, and colleagues have shown the opposite result, namely that the N2pc is unaffected by stimulus saliency. Eimer and Kiss (2008) presented spatially uninformative color cues prior to a visual search task. They found that an N2pc was only elicited by the cues if color was the task-relevant dimension (i.e., color cues and a color search task). No N2pc to these color cues was found when the subsequent search task required line orientation discrimination instead. This study thus suggested that the N2pc is elicited only by task-relevant stimulus properties. In a follow-up study, Eimer et al. (2009) furthermore showed that non-singleton task-relevant cues elicited only a minimally smaller N2pc than singleton cues, which argues against the idea that the N2pc is sensitive to stimulus saliency. Similar findings have also been reported in singleton search without cues, in rapid serial visual presentation, and in displays with more than one (salient) task-irrelevant stimulus (Akyürek et al., 2010a,b; Kiss et al., 2008a,b; Leblanc et al., 2008).

The debate on attentional capture is thus not quite settled, and these ERP studies have not fully resolved the issue of when stimulus-driven or task-contingent capture is dominant. The lack of a decisive answer to this question might be due to variations in the experimental approach taken in the previous studies. In particular, previous work has not fully explored the issue of stimulus specificity. The studies to date have relied on relatively variable designs, in which either target or distractor stimuli had variable properties. This may have affected attentional deployment. For instance, Hickey et al. (2006) showed that attention may be captured by task-irrelevant stimuli, but in their design the target was defined ambiguously. As pointed out by Eimer and Kiss (2008), this may have induced the adoption of a broad task set. In such cases, the observer cannot form a precise target template, and may be prone to adopt a selection criterion that is too liberal. In other words, uncertainty regarding the target specification may lead to an overestimation of stimulus-driven effects. This prompts the question of what will happen if the target is defined unambiguously, that is, exclusively at the feature level. To clarify, such a definition also entails that the target can only be found if a feature-specific search template is used, rather than a dimension-specific one. For example, a target may be found if the observer is looking for blue stimuli (feature-specific), but not if looking for colored stimuli (dimension-specific)—because there may be stimuli in the search array that fit the latter criterion.

Eimer et al. (2009) partially addressed this issue using a specific target template. Their results indeed suggested that attention is drawn exclusively to a pre-defined feature, such as a specific color. In their design, however, the distractor stimuli were variable (i.e., they were of several colors), which may have prevented their participants from using a specific distractor template. There is evidence to suggest that such a template may be dissociated from a target template, and may affect different functional areas of the brain, related to spatial filtering (Akyürek et al., 2010a,b,c). Thus, participants may have been forced to rely on the target specification only, a search mode which could have biased the deployment

of attention. The effect of having a specific distractor template on attentional deployment thus remains unknown.

When addressing the issue of stimulus specificity, one has to be mindful of other potential design pitfalls as well: first, it is important to keep the number of salient stimuli equal across all conditions, to prevent singleton counting. If observers are able to predict the current condition (i.e., whether it is a target trial or not), they may make use of these clues to deploy attention strategically. Second, in some studies, the target in the search display could be found by attending to anything salient, as the target was the sole deviant object in the display. This strategy has been named singleton search mode (Bacon and Egeth, 1994). Because this mode entails that any salient stimulus is task-relevant, it is mostly driven by bottom-up stimulus factors. Third, if the target is unique on a particular feature dimension, the entire dimension becomes task relevant, and any signal on that dimension will lead to the target. A design of this type may thus over-emphasize dimensional bias in attentional selection.

To satisfy these requirements, the present study settled on a design that dissociated between targets, nontargets, and distractors. The targets were clearly specified as having one particular color, so that no uncertainty regarding the target template existed, and thus there was no need to adopt a broad selection strategy. The distractors consisted of salient stimuli on the same feature dimension (color) as the target, which were always shown in the opposite visual hemifield. These served as a permanent baseline against which the other stimuli were pitted, and required spatial filtering of the search array. Thus, if the target was of one particular color (e.g., always blue), it would always be accompanied by a distractor in the opposite visual field in another color (e.g., always green; these colors were counterbalanced). This meant that a deliberate strategy to attend to any salient signal on the color dimension, or just any salient stimulus (i.e., singleton search mode) would be ineffective. The nontargets were also accompanied by the distractor stimuli in the opposite visual hemifield. There were furthermore two kinds of nontargets; color nontargets and line orientation nontargets. These allowed a measurement of attentional allocation towards stimuli on the task-relevant dimension (color), and towards those who were on a task-irrelevant dimension (orientation), while keeping the distractor baseline identical.

With regard to the issue of attentional capture and stimulus specificity, two predictions can thus be made. (1) When targets have constant and specific properties, top down control should be optimal (and feature specific rather than dimension specific) and capture effects of simultaneous task-irrelevant distractors should be minimized. Accordingly, targets were expected to be easy to select and to elicit an N2pc of large amplitude. (2) When distractors have constant and specific properties, these should be filtered out with relative ease. This should further facilitate the selection of simultaneous targets, and should also cause nontargets to attract more attention, as these were more variable than the permanent distractors (i.e., there were two kinds), and were thus less well specified. Thus, nontargets may elicit an N2pc, which should, however, be smaller than that of the targets (cf., prediction 1). Further to that, the N2pc towards nontargets was expected to vary depending on the feature dimension they were defined in; the task-relevant feature dimension of color should elicit increased N2pc amplitude compared to nontargets defined in the task-irrelevant dimension of orientation.

## 2. Methods

### 2.1. Participants

Sixteen right-handed students (14 female, 2 male) at the Ludwig Maximilian University Munich participated for course credit or monetary payment. Participants were unaware of the purpose of the experiment and had not taken

part in similar experiments in the lab before. Mean age was 23.8 years (range 20–27 years).

## 2.2. Apparatus and stimuli

Participants were individually seated in a comfortable chair in an electrically shielded and sound attenuated testing chamber that was dimly lit. Stimuli were presented on a Viewsonic 19" CRT screen, refreshing at a frequency of 100 Hz at a resolution of 800 by 600 pixels in 16 bit color, which was placed at approximately 80 cm distance directly in front of the participants. Responses were registered on a USB keyboard sampling at 125 Hz. Stimulus presentation was controlled by an Intel Core 2 Duo computer with discrete graphics running E-Prime 1.2 (Psychology Software Tools, Pittsburgh, USA). Search displays consisted of an array of black vertical lines on a white background. The arrays were centered on the screen and consisted of 21 lines of 30 by 5 pixels arranged in a circular array with 50 pixels inter-stimulus distance. For each line in the array a random displacement jitter of 0–5 pixels in both horizontal and vertical directions was used. Two salient stimuli were presented in each array, one of which, the permanent distractor, was always a line in a task-irrelevant color, either green or blue (counterbalanced with the target color across participants). Depending on the experimental condition, the second salient stimulus was either a line in the target color (green or blue), a line in the designated nontarget color (red), or a line tilted in either the left or the right direction (its endpoints were displaced by 10 pixels on the horizontal plane). All of the chosen colors were isoluminant. The two salient stimuli could appear at any lateralized display location, but always appeared on locations that were each others mirror on the vertical axis.

## 2.3. Procedure and design

Trials were randomly distributed over four blocks, each of which contained 300 trials. The total of 1200 trials was preceded by a practice block of 30 trials. Participants had the opportunity to take a break between blocks. Trials were evenly divided over the three conditions of the experiment: target trials, color nontarget trials, and orientation nontarget trials. Note that color nontarget refers to the presentation of a stimulus with the designated nontarget color (red), and not of one in the task-irrelevant color (green or blue) as this latter permanent distractor stimulus was shown in all trials. In the discussion it is important to be mindful of this three-way dissociation between target, nontarget, and distractor stimuli: there were targets as well as nontargets, and both of these were always accompanied by distractors in the other half of the visual field. Each trial started with a fixation cross ("+") in the center of the screen, which was visible for a variable duration of 600–1000 ms. The search array was then displayed for 400 ms and followed by a blank screen for 600 ms. Subsequently performance feedback was given for 200 ms, and the next trial commenced. The task for the participants was to indicate whether a target stimulus had been shown, or not. They could indicate so with the fingers of their right hand by pressing the 1 (present), or 2 (absent) key on the numeric pad of the keyboard. Fig. 1 shows a schematic representation of the trial structure. In the analyses, responses below 100 ms were discarded (0.6%), and when sphericity was a concern the degrees of freedom were adjusted using the Greenhouse–Geisser epsilon correction.

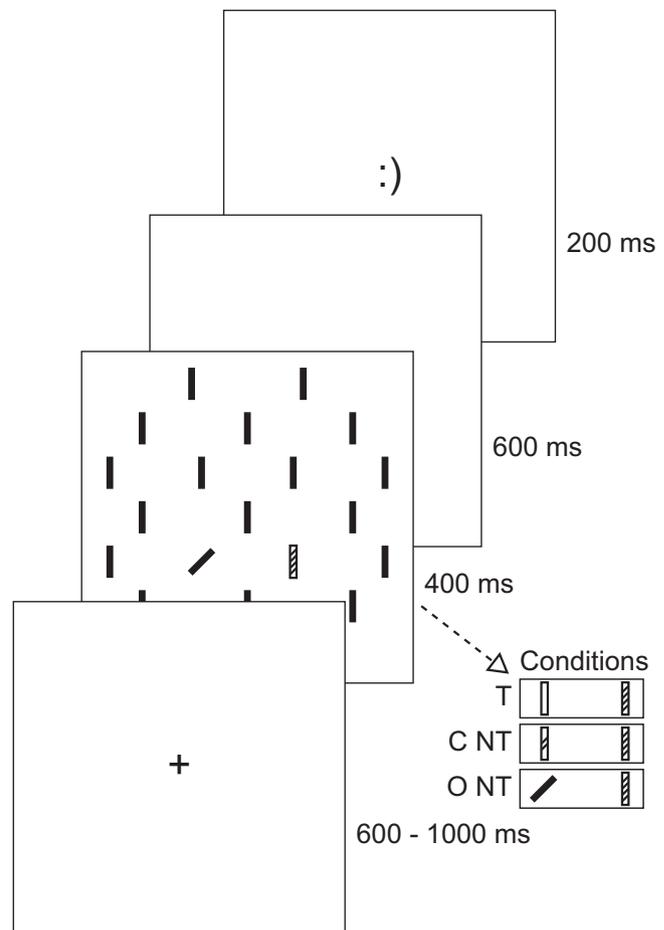
## 2.4. Electrophysiological recording and data analysis

Locally pre-amplified Ag–AgCl electrodes recorded the EEG from 64 positions that were laid out in an elastic cap according to the extended international 10–20 system (actiCAP; Brain Products, Munich, Germany). The electrodes were referenced to FCz and re-referenced offline to the average of both mastoids. Horizontal and vertical EOG were recorded from electrodes near the outer canthi of the eyes, and above and below the left eye. Impedances were kept below 20 k $\Omega$ . The amplifier used a 0.1 Hz high-pass filter. EEG was digitized at a frequency of 500 Hz.

The data were filtered off-line with a 40 Hz low-pass filter. For each electrode, trials that showed amplitudes exceeding  $\pm 80 \mu\text{V}$ , voltage steps exceeding  $\pm 50 \mu\text{V}$  between two sampling points, or voltages lower than  $0.10 \mu\text{V}$  for a 100 ms interval were excluded from further analysis. Ocular artifacts (blinks and eye-movements) were corrected by applying the Gratton–Coles procedure (Gratton et al., 1983). Baseline correction was done using a 200 ms pre-stimulus interval. EEG was averaged off-line in 1000 ms epochs, starting 200 ms prior to the onset of the search array and ending 800 ms afterwards.

Repeated measures analyses of variance (ANOVA's) were performed for mean amplitude values in the following time windows: P1 (100–130 ms after stimulus onset), N1 (130–160 ms), N2p (220–260 ms), and P3 (310–430). Two lateral components were examined; the lateralization in the N1 time range (120–170 ms), and the N2pc (190–270 ms). In the interest of brevity, the first of these is referred to as "N1pc" (cf., Wascher and Beste, 2010), simply because it seemed to fall in the corresponding time range. The following electrodes were selected, in line with standard practice: POz (P1, N1, and N2p), PO7/PO8 (N1pc and N2pc), and Pz (P3). To compute the N1pc and N2pc, ipsilateral waveforms (i.e., recorded from the left hemisphere electrode site when the singleton was in the left visual field, and the same for the right hemisphere site and right visual field) were subtracted from contralateral waveforms (i.e., left site and right visual field, and right site and left visual field).

One reason to select the early components (P1, N1, and N1pc) for analysis was to investigate potential effects elicited by the physical appearance of the stimuli.



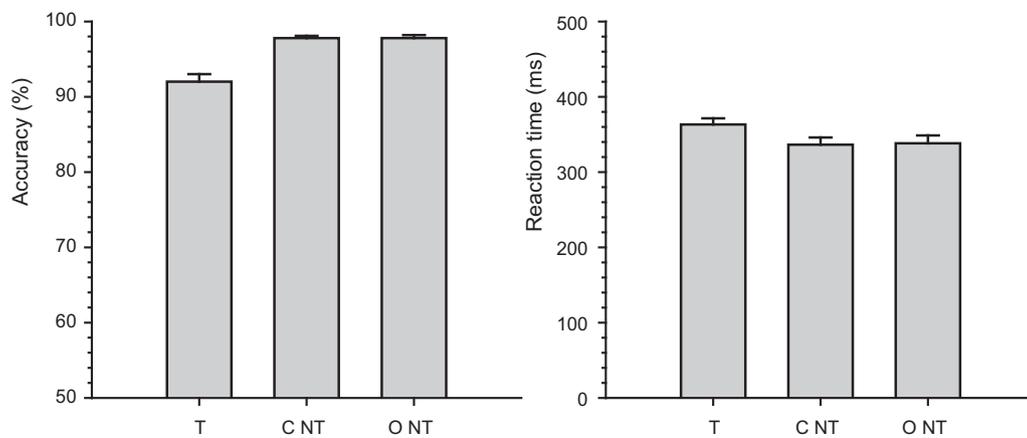
**Fig. 1.** The experimental procedure. After a fixation cross of 600–1000 ms duration, the search array is displayed for 400 ms. The array consisted of black vertical lines, and one line in the task-irrelevant color (permanent distractor; shown here with a stripe pattern). Additionally, either a line in the target color (target), a black tilted line (orientation nontarget), or a line in the nontarget color (color nontarget) appeared. The distractor color is indicated here with a dense stripe pattern fill, the nontarget color with a sparse pattern, and the target color with no fill. A blank screen ensued for 600 ms, followed by a 200 ms feedback display. For correct responses “:)” was shown, and for incorrect or missing responses “:(” in the lower right, the experimental conditions (i.e., the two singleton types) are shown schematically. Stimulus side and task-relevant color were randomly distributed and counterbalanced. Abbreviations: “T” stands for target, “C NT” stands for color nontarget, and “O NT” stands for orientation nontarget.

As can be seen from Fig. 1, the search arrays were largely identical across all trial types, and salient stimuli were balanced across the visual field. However, target and nontarget stimuli were different, although target and nontarget colors were isoluminant. In order to investigate to what extent the physical discrepancy between the stimuli affected the ERP, early ERP components were taken into the analysis. Further downstream, the N2 and N2pc were selected to gauge attentional processing. Components in this time range have been shown to be independent of even relatively strongly imbalanced stimulus configurations (Hickey et al., 2009). Finally, the P3 was selected for analysis to highlight the final stages of selection, and its eventual outcome.

## 3. Results and discussion

### 3.1. Behavior

Behavioral performance was clearly dependent on the experimental conditions. Accuracy,  $F(1, 19) = 53.56$ ,  $MSE = .001$ ,  $p < .001$ , as well as reaction time,  $F(1, 18) = 23.16$ ,  $MSE = 264.185$ ,  $p < .001$ , were modulated. Average accuracy in the target condition was 92%, compared to 97.8% in the color nontarget condition, and an identical 97.8% in the orientation nontarget one. Post hoc comparisons of



**Fig. 2.** Behavioral performance. The left panel shows accuracy (% correct), and the right panel shows reaction time (ms). Error bars represent one standard error of the mean.

the means showed that the target condition differed clearly from the others ( $t = 7.39$  for the color nontarget pair-wise comparison, and  $t = 7.95$  for the orientation nontarget pair), while the nontarget conditions did not differ reliably ( $t < 1$ ). The left panel of Fig. 2 plots accuracy for each of the experimental conditions.

Similarly, reaction time was higher in the target condition (363 ms) than it was in the color nontarget (336 ms) and orientation nontarget (338 ms) ones. Pair-wise comparisons again showed that only the target condition differed from the others ( $t = 5.52$  and  $t = 4.51$ ), and the nontargets did not differ from each other ( $t < 1$ ). Thus, behavioral responses indicated that detecting a target was harder than detecting a nontarget of either kind. The right panel of Fig. 2 plots reaction times for each of the conditions.

### 3.2. Electrophysiology

Neither the analysis of the P1 ( $F < 2.5$ ), nor that of the N1 ( $F < 1$ ) showed an effect of the experimental condition, suggesting that physical differences between stimuli did not have clearly detectable effects on these components. Mean P1 amplitude was  $.62 \mu\text{V}$  ( $SE = .87 \mu\text{V}$ ) for targets,  $.29 \mu\text{V}$  ( $SE = .96 \mu\text{V}$ ) for color nontargets, and  $.57 \mu\text{V}$  ( $SE = .91 \mu\text{V}$ ) for orientation nontargets. Mean N1 amplitude was  $-.39 \mu\text{V}$  ( $SE = .83 \mu\text{V}$ ) for targets,  $-.15 \mu\text{V}$  ( $SE = .79 \mu\text{V}$ ) for color nontargets, and  $-.35 \mu\text{V}$  ( $SE = .79 \mu\text{V}$ ) for orientation nontargets. The top left panel of Fig. 3 shows the mean amplitude recorded at the POz electrode.

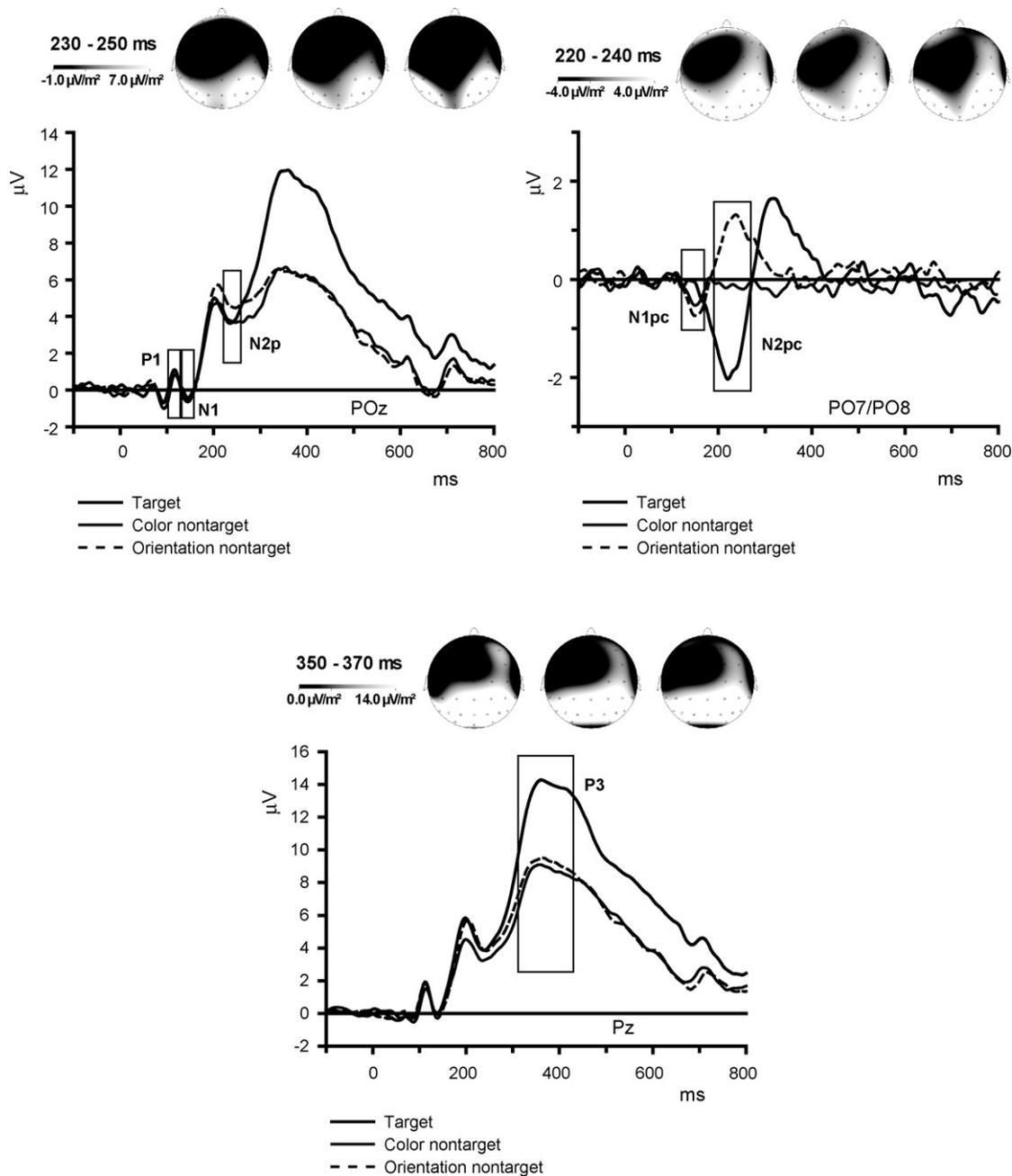
There was, however, evidence for an early effect in the lateralized ERP. Prior to the onset of the N2pc, the N1pc amplitude computed between 120 and 170 ms post-stimulus revealed a significant effect of the experimental condition,  $F(2, 30) = 4.32$ ,  $MSE = .128$ ,  $p < .05$ . Mean amplitude was lowest for target stimuli ( $-.16 \mu\text{V}$ ,  $SE = .08 \mu\text{V}$ ), reflecting a lack of a detectable lateralization on this component. This was not the case for color nontargets ( $-.35 \mu\text{V}$ ,  $SE = .11 \mu\text{V}$ ) and orientation nontargets ( $-.52 \mu\text{V}$ ,  $SE = .14 \mu\text{V}$ ), both of which showed a small but clear peak, as shown in the top right panel of Fig. 3. *T*-tests confirmed these were significantly different from zero ( $t = 3.30$ ,  $p < .005$ , and  $t = 3.72$ ,  $p < .005$ , respectively). Post hoc comparison of the means showed that only the difference between targets and orientation nontargets was reliable,  $t = 2.92$ ,  $p < .05$  (also surpassing the Tukey criterion,  $t > 2.46$ ). Thus, initial lateralized activity was more evoked by orientation nontargets than by targets. Since the orientation nontargets were the most unique type of singleton in the present experiment, this initial response might be associated with the conspicuity resulting from that fact. As it may also be possible that the distinct physical appearance of the orientation nontargets caused this effect, caution with its interpretation is warranted although there has been strong

evidence that lateralized effects of P1/N1 components are associated with attentional processing (for an overview, see Hillyard and Anllo-Vento, 1998; see also Section 4 below).

The most prominent lateral effect was observed at the N2pc,  $F(1, 19) = 9.99$ ,  $MSE = 3.644$ ,  $p < .005$ . N2pc amplitude was highest (i.e., most negative) following target stimuli ( $-1.5 \mu\text{V}$ ,  $SE = .5 \mu\text{V}$ ). Color nontargets did not seem to elicit a proper N2pc, and amplitude was close to zero ( $-.13 \mu\text{V}$ ,  $SE = .12 \mu\text{V}$ ). Orientation nontargets did elicit an N2pc wave, which was, however, of the opposite polarity ( $.86 \mu\text{V}$ ,  $SE = .3 \mu\text{V}$ ). As might be suspected from the waveforms shown in the top right panel of Fig. 3, comparison of the means confirmed that all three means were reliably different from one another ( $t = 2.53$  for target and color nontarget,  $t = 3.56$  for target and orientation nontarget, and  $t = 3.42$  for color and orientation nontargets). Two possible scenarios might account for the lack of an N2pc for color nontargets. The first is that attention was not drawn to the color nontarget, and neither to the permanent distractor in the task-irrelevant color (i.e., attention stayed in the middle of the search array). The second is that attention was drawn to either singleton with about equal frequency, thereby cancelling each other out in the average amplitude of the N2pc. As noted, orientation nontargets elicited an N2pc wave of opposite polarity. This reversal indicated that attention as indexed by the N2pc was not drawn towards the stimulus in the contralateral visual field, but rather to the ipsilateral field. In other words, it went towards the permanent distractor and not to the orientation nontarget. In summary, the N2pc seemed most sensitive to the separation of target and nontarget singletons as it showed a differential pattern for target, for a nontarget from the target dimension, and for a nontarget from a different dimension.

Modulation of the N2p was also observed,  $F(2, 30) = 3.68$ ,  $MSE = .943$ ,  $p < .05$ . N2p component amplitude averaged  $3.9 \mu\text{V}$  ( $SE = .87 \mu\text{V}$ ) for targets,  $3.83 \mu\text{V}$  ( $SE = 1 \mu\text{V}$ ) for color nontargets, and was clearly less negative for orientation nontargets, at  $4.67 \mu\text{V}$  ( $SE = .94 \mu\text{V}$ ). Individual comparisons showed that targets and color nontargets did not differ ( $t < 1$ ), but that targets and orientation nontargets ( $t = 2.24$ ), and color and orientation nontargets ( $t = 2.5$ ) did. It would thus seem that the N2p is sensitive to the specific target–nontarget distinction, even though the N2pc, which peaked slightly earlier, showed a more gradual response suggesting that a more specific target–nontarget distinction had already been made.

Finally, modulation of the P3 component was observed, which was perfectly in line with the behavioral results,  $F(1, 17) = 23.03$ ,  $MSE = 8.571$ ,  $p < .001$ . Targets elicited the highest P3 amplitude ( $13.31 \mu\text{V}$ ,  $SE = 1.53 \mu\text{V}$ ), while color and orientation nontargets showed clearly lower amplitudes ( $8.48 \mu\text{V}$ ,  $SE = 1.04 \mu\text{V}$ , and  $8.95 \mu\text{V}$ ,  $SE = 1.03 \mu\text{V}$ , respectively). Individual comparisons



**Fig. 3.** Waveforms recorded at the Pz and POz electrodes (in  $\mu\text{V}$ ), as well as contra-minus ipsilateral difference waveforms recorded from PO7/PO8 ( $\Delta\mu\text{V}$ ). Stimulus onset is set at 0 ms. Topographical maps were constructed using spherical spline interpolation and represent a 20 ms average centered on the observed waveform peaks. For each graph, from left to right the maps represent targets, color nontargets, and orientation nontargets.

revealed that the nontargets did not differ from each other ( $t < 1.6$ ), whereas targets and color nontargets ( $t = 4.99$ ) and targets and orientation nontargets ( $t = 4.81$ ) did. Thus, the P3 mirrored the behavioral pattern in that targets were dissociated from nontargets of any kind. The bottom panel of Fig. 3 shows the waveforms recorded at the Pz electrode.

#### 4. General discussion

The ERP components measured in the present study showed that task-contingent attentional control was active throughout the perceptual process, with clear effects of dimensional selectivity, despite the constant presence of distraction on the task-relevant

dimension. In the following, the main findings are discussed and interpreted in more detail.

##### 4.1. Behavior

Behavioral performance clearly showed that the task design was effective. Finding the target stimulus was not easy; accuracy on target present trials was lowest and reaction time was highest. This might be attributed to the presence of a permanent distractor in the search array, which complicated search. Alternatively, the behavioral outcome might also have reflected a stimulus frequency effect or an associated degree of response bias. The target present response was the most infrequent, which means that response

perseverance was stronger for target absent responses and this might have reduced performance on target present trials.

#### 4.2. P1 and N1

The earliest components of the regular (i.e., non-lateralized) ERP, the P1 and N1, were not affected by the experimental manipulations, and were similar for all types of trials. The lateralized ERP did show a remarkably early effect, with a small but clearly visible peak at just over 150 ms post-stimulus, presumably reflecting what might be called an N1pc. The differential amplitude of the lateral component was maximally different between targets and orientation nontargets (see Fig. 3). It would thus seem that orientation nontargets did receive some early (potentially attentional) selection, which may provide some support for theories that suppose the existence of an early, stimulus-driven sweep of attention (e.g., Theeuwes, 2010). However, as has been noted, the degree to which this early difference is attentional in nature cannot be established presently. The possibility remains open that differences on the stimulus level might underlie the deflections here. Importantly, the pattern observed here did not replicate onto later components (such as the N2pc), which confirmed the independence between the processes measured in these time windows. It is likely that several factors contributed to the observed N1pc amplitude difference. First, it might be that the tilted line segment was simply more outstanding in the visual field than the colored lines. Second, the saliency of the tilted lines may have been increased because it was uniquely different from the others, being defined on a dimension clearly distinct from the target (i.e., orientation vs. color) and thereby being easy to reject.

It also has to be noted, however, that although comparison of the individual means could not provide a definite confirmation, there was a similar and significant (i.e., from zero) deflection in the N1pc range for color nontargets, which shared their feature dimension of relevance (i.e., color) with the targets. This tentative result casts some doubt on the idea that the dimension difference was the only reason for the modulation here. Either way, the early modulation of the lateralized ERP indicated that the (orientation) nontarget stimuli were somehow special at this early phase of perceptual processing.

One might furthermore speculate about a possible relation of the present modulations to the selection negativity (SN). The SN is an additional amplitude differential over posterior regions, starting at about 120 ms and lasting until 300 ms or later (e.g., Anillo-Vento and Hillyard, 1996). It is typically elicited by tasks that require the observer to select targets by nonspatial features, which is similar to the requirements of the present experiment. Even though the selectivity at this early stage of processing might occur in a similar time window as the SN, the present results do not lend themselves very well to an explanation in terms of a single negative component, as the N2pc component showed different modulations, as discussed in more detail below. Furthermore, there was no sign of an effect on non-lateral components, nor of any additional components next to the expected N1 and N2.<sup>1</sup>

<sup>1</sup> It has also been stated that a contralateral boost of N1 amplitude might reflect an attentional boost signal, whose function it is to highlight a particular (task-relevant) region of space (Hillyard et al., 1998). At first glance, such task-related selectivity might seem to conflict with the absence of task-related modulations in the present study (unless the absence of a deflection is taken as such). It is clear, however, that the (a priori) selection of a specific location is a requirement for this type of selectivity to occur. In the present study, the design of the search task prohibited the exploitation of this boost function, as the present stimuli of interest were not defined by their unique special location. Therefore, the seemingly stimulus-driven nature of the presently observed modulations is not in conflict with the early attentional selectivity observed with other experimental tasks.

#### 4.3. N2(pc)

As previously alluded to, the N2pc, which developed very rapidly after the N1pc, showed a clearly different pattern than that of the earlier component. This finding reinforces previous demonstrations of the independence of this component from physical differences between stimuli (Eimer et al., 2009; Hickey et al., 2009), as the present deflections did not mirror those found in the N1 range. Each type of trial elicited an entirely different response from the N2pc component. There was an N2pc of high amplitude towards target stimuli, but no N2pc whatsoever towards color nontargets was observed in the average. Note that this is not to say there was no N2pc at all in this condition, as the average might have consisted of a similar number of trials with N2pc deflections towards the color nontarget and towards the permanent color distractor on the other side of the visual field (see Fig. 1). In any case, this result can be interpreted as an indication that neither of these singletons attracted more attention than the other. As none of the singletons shared the exact target feature, neither of them was preferentially attended, despite the constant nature of the distractor. On the trials with orientation nontargets a positive deflection rather than a negative one was observed, indicating that instead of going towards the orientation nontarget, attention went towards the stimulus on the opposite side of the visual field, namely the permanent distractor. Note that the positivity of this component is a result of the computational procedure, which was locked to the (non-) target in the opposite visual field. In essence, this deflection can be thought of as an N2pc towards the distractor. Alternatively, it is possible to interpret this component as a reflection of possible spatial suppression mechanisms found to elicit a lateral, positive deflection (labeled Pd; distractor positivity) in displays containing both target and distractor stimuli (Hickey et al., 2009). This suppression may have been afforded by the specificity of the distractor. However, it should be noted that the present task only required target detection rather than identification, which casts some doubt on the interpretation of this waveform in terms of the Pd component, because the Pd is not typically associated with detection tasks (Sawaki and Luck, 2010).

The N2pc thus showed a strong bias towards task-relevant stimuli, a category which could include even the permanent distractor stimuli that only shared the dimension with the actual target. Whenever an actual target was shown, however, there was no sign of any hesitation between these two. The strength of the dimensional preference was highlighted by the ability of the stimuli in the task-irrelevant color to elicit an inverted (ipsilateral) N2pc, in spite of being present on every trial, and therefore also being unremarkable from a trial frequency perspective. Taken together, N2pc amplitude was maximally dissociative for the stimuli in the present experiment. Each type of trial elicited clearly different N2pc amplitude. This result extends the findings of Eimer et al. (2009), who showed feature-specific modulation of the N2pc in a design with variable distractors.

The strongly task-related effects on the N2pc component are in accord with previous reports on the selectivity of this component in singleton search studies. Early studies of the N2pc by Luck and Hillyard (1994a,b) already highlighted that the N2pc is sensitive to target/nontarget differences, and is affected by same-dimension perceptual difficulty. Similarly, previous work on singleton search by the present authors has shown that an N2pc is elicited by nontargets defined in the task-relevant dimension, but not by nontargets defined in a task-irrelevant dimension (Akyürek et al., 2010a,b,c; Schubö and Müller, 2009). This pattern of task-dependent selectivity seems to be stable across different experimental paradigms as well, such as cued visual search and RSVP (Eimer and Kiss, 2008; Kiss et al., 2008a,b; Leblanc et al., 2008). The current results extend these findings to 'competitive'

search tasks, in which multiple salient stimuli appear simultaneously.

A notable discrepancy does exist between these studies as well as the present findings, and those of Hickey et al. (2006). Recall that in the critical condition in Experiment 2 of their study observers were looking for targets defined by shape (square vs. round) in circular search arrays. Distractor items (color singletons) were simultaneously presented in the opposite hemifield. Hickey and colleagues reported an apparently small but significant increase of the negativity contralateral to this distractor item, in what they defined as the early time window of their N2pc component (220–265 ms), and claimed that this was indicative of an early N2pc towards the task-irrelevant item. Eimer and Kiss (2008) stated that the discrepancy between their findings and those of Hickey et al. (2006) might be due to differences in their experimental paradigms. While Eimer and Kiss used a cued search paradigm, Hickey and colleagues used a two-singleton (simultaneous) search task. The present study is obviously similar to the latter design, yet the present results do not replicate those of Hickey et al. (2006), neither when a target appeared simultaneously with the distractor, nor when an orientation nontarget appeared. The critical difference seems to be that the target was unambiguously specified in the present study. The conclusion follows that having an uncertain target template must have led to a liberal search strategy in the Hickey et al. (2006) study, thereby triggering a degree of attentional capture by salient distractor stimuli (a possibility previously coined by Eimer et al., 2009).

The next component of the ERP studied in the present study, the posterior N2 component (N2p), which broadly fell in the same time range as the N2pc, did not show a distinct response to each of the target and nontarget trials. Targets and color nontargets showed higher N2p amplitude than orientation nontargets. It would thus seem that this component was only sensitive to the task-relevant dimension, without regard for the actual target and nontarget colors. With regard to achieving the desired selection and accomplishing the task, the modulation of the N2p looked like a step sideways, in comparison to the selective response of the N2pc. One might speculate that the perceptual system uses multiple routes to process a visual stimulus, and that the effect observed at the N2p can be seen as another source signal, highlighting just the dimensional aspect of the stimuli, which is used as input for further processing next to that of other sources (i.e., those reflected by the N2pc).

#### 4.4. P3

The last component of the measured ERP, the P3 component, showed perfect selectivity and corresponded with the desired behavioral task output. The targets elicited the highest amplitude, and the color nontargets were clearly below that, together with the orientation nontargets. In other words, a classifier system that would use P3 amplitude as input could achieve the desired behavioral task performance, and dissociate between the responses that were required. Without seeking to draw strong conclusions with regard to what the P3 might represent (instead see Polich, 2007; Verleger et al., 2005), it seems safe to state that in the present task the P3 can be seen as reflecting the end result of selection.

#### 4.5. Conclusion

Taken together, the results suggested that the response of the perceptual system to the dual singleton displays of the present study was strongly driven by task contingency. There was evidence for dimensional selectivity of the N2p and N2pc components of the ERP, despite the fact that none of the search displays would become easier from using such a search strategy, since the target dimension

was never unique and did not cue the presence of the target. In this light, searching a target via dimensional selectivity seems to be an automatic process that takes place even when it may not be the optimal strategy to solve the task or indeed may hinder it. This corroborates evidence for differential functional involvement of brain areas for target selection and distractor suppression (Akyürek et al., 2010a,b,c).

The present results also offer an account for the seemingly contradictory results in the literature showing evidence for both stimulus-driven and of task-contingent attentional capture at the N2pc (Eimer and Kiss, 2008; Hickey et al., 2006). Perceptual processing seems to be sensitive to having unambiguous target and distractor templates; without that certainty a more liberal search strategy is used, which opens the door for stimulus-driven effects. Some support for this account is given by previous behavioral work that has shown how the configuration of the experimental task may affect the search strategy used by the observer, which in turn strongly guides attentional deployment (Bacon and Egeth, 1994).

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