Irrelevant Singletons in Visual Search Do Not Capture Attention but Can Produce Nonspatial Filtering Costs

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Abstract

■ It is not clear how salient distractors affect visual processing. The debate concerning the issue of whether irrelevant salient items capture spatial attention [e.g., Theeuwes, J., Atchley, P., & Kramer, A. F. On the time course of top–down and bottom–up control of visual attention. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive performance* (pp. 105–124). Cambridge, MA: MIT Press, 2000] or produce only nonspatial interference in the form of, for example, filtering costs [Folk, Ch. L., & Remington, R. Top–down modulation of preattentive processing: Testing the recovery account of contingent capture. *Visual Cognition, 14,* 445–465, 2006] has not yet been settled. The present ERP study examined deployment of attention in visual search displays that contained an additional irrelevant singleton. Display-locked N2pc showed that attention was allocated to the target and not to the irrelevant singleton. However, the onset of the N2pc to the target was delayed when the irrelevant singleton was presented in the opposite hemifield relative to the same hemifield. Thus, although attention was successfully focused on the target, the irrelevant singleton produced some interference resulting in a delayed allocation of attention to the target. A subsequent probe discrimination task allowed for locking ERPs to probe onsets and investigating the dynamics of sensory gain control for probes appearing at relevant (target) or irrelevant (singleton distractor) positions. Probe-locked P1 showed sensory gain for probes positioned at the target location but no such effect for irrelevant singletons in the additional singleton condition. Taken together, the present data support the claim that irrelevant singletons do not capture attention. If they produce any interference, it is rather due to nonspatial filtering costs. ■

INTRODUCTION

Humans need to deal with distraction in everyday situations. Attention can be captured in a bottom–up/exogenous manner (Wolfe, 1994; Posner, 1980) to an item/location in space with salient characteristics, that is, characteristics that highly contrast with the environment. The question of interest is whether this type of attention allocation can be controlled by top–down processes, that is, whether humans are able to focus on the relevant characteristics and ignore salient items that are irrelevant to their task at hand (Wolfe, Butcher, Lee, & Hyle, 2003; Wolfe, 1994). This question has been addressed by many researchers who, on the one hand, provided evidence for a strong impact of top–down control (Wykowska & Schubö, 2010; Eimer & Kiss, 2008; Folk & Remington, 1998, 2006; Müller, Reimann, & Krummenacher, 2003; Kim & Cave, 1999; Bacon & Egeth, 1994; Folk, Remington, & Johnston, 1992) and, on the other, for the strength of exogenous attention capture (Hickey, McDonald, & Theeuwes, 2006; Theeuwes, Atchley, & Kramer, 2000; Theeuwes, 1992).

Bottom–Up Driven Attentional Capture versus Top–Down Control

In series of experiments, using a so-called *additional singleton paradigm*, Theeuwes et al. (2000) and Theeuwes (1992) showed performance costs in a situation when a predefined target was accompanied by a more salient singleton—relative to a condition when target was presented alone. Theeuwes concluded that attention must have been first deployed to the more salient but irrelevant item producing the RT costs. Therefore, according to Theeuwes, attention is deployed to the items in the visual field in the order of decreasing saliency irrespective of their (ir)relevance to the task at hand.

On the contrary, Folk and Remington (1998, 2006) and Folk et al. (1992) claim that the allocation of attention is dependent on the attentional set of the observer. Folk et al. used a *spatial cueing paradigm* in which a cue display was presented before the target display. The cue display usually contained a salient singleton that was uninformative with respect to subsequent target location. Therefore, participants should have shown no incentive to allocate attention to the salient singleton of the cue display. Participants were to detect a target of a predefined feature (e.g., color) and to discriminate the identity of a symbol that was presented within the target item. Folk et al. found that performance in symbol discrimination was better when the target was presented at the previous location of the cue singleton (the so-called *spatial validity effect*), but only if the singleton shared the characteristics of the target. The authors concluded that attentional capture is contingent on the top–down attentional set of the observers. Lien, Ruthruff, Goodin, and Remington (2008)

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provided electrophysiological evidence for this claim. They used a similar cueing paradigm as Folk et al. (e.g., Folk & Remington, 1998, 2006; Folk et al., 1992) and focused on the N2pc component that reflects the difference between mean amplitudes of the ERPs observed at electrode sites contralateral and ipsilateral to an attended item in the visual display. The N2pc is observed at posterior-occipital electrodes about 180–300 msec after display presentation (Eimer, 1996; Luck & Hillyard, 1994) and is considered to reflect deployment of attention in a visual scene. Lien et al. observed N2pc effects of attentional capture to the irrelevant and uninformative cue only if it shared target characteristics, that is, when it was the same color as the target, which supported the *contingent capture* account. Similar results were observed by Eimer and Kiss (2008) who also showed contingent capture effects on N2pc.

Wykowska and Schubö (2010) examined the potency of top–down control in a study with the use of ERP methodology in which a visual search with a postdisplay probe presentation was used (following the logic of a paradigm used by Kim & Cave, 1999). Participants were asked to search for a shape target. In some trials, a more salient irrelevant color singleton was presented. The search display was followed by a probe item presented after two different SOAs. The probe could be located at a previous target position, an irrelevant singleton position, or a neutral position of one of the distractors. Results revealed that the N2pc time locked to the search display was present for the target but not for the irrelevant singleton. Moreover, the P1, a component related to the sensory gain control (e.g., Luck & Hillyard, 1995; Luck, Fan, & Hillyard, 1993), time locked to probe onset, increased when the SOA between search display and probe was increased, and was modulated with respect to the probe position: probes presented at the target location elicited a more enhanced P1 component compared with probes presented at other neutral locations. This suggested some carryover enhanced neural activation for probes presented at the previously attended location (target) as compared with presumably non-attended locations (neutral distractors). This effect was neither observed for the location of the irrelevant singleton nor was it found in the short SOA condition. In sum, the study showed that with time, top–down control guided spatial attention to the task-relevant target and not to the more salient distracting item.

Do Irrelevant Singletons Capture Spatial Attention or Produce Only Filtering Costs?

Theeuwes et al. (2000) and Hickey et al. (2006) argued against the contingent capture perspective and other claims concerning top–down control over bottom–up processing by stating that attention is automatically and necessarily driven to the most salient item within the first 100 msec of processing to be subsequently rapidly disengaged and reoriented to target items. Therefore, the results brought forward as evidence for top–down control might in fact miss the effects of attentional capture that might occur in brief time intervals subsequent to stimulus presentation. To support this thesis, Theeuwes et al. conducted a study using the additional singleton paradigm in which the onset latencies of the target relative to the onset of the additional singleton were varied. Results showed that the presence of additional singleton produced RT costs, but only if its onset was up to 100 msec earlier than the onset of the target. At longer SOAs, there was no cost of the additional salient singleton. As a reply to this argument, Folk and Remington (2006) argued that results of Theeuwes et al. do not necessarily support attentional capture effects to the irrelevant singleton but they can still be interpreted in line with the idea of filtering costs (Folk & Remington, 1998, 2006) produced by the additional singleton. Such filtering costs might result from a competition between two pop-out items, which delay the deployment of attention to the target. This would not necessarily imply that attention is allocated to the irrelevant singleton before it is allocated to the target. According to Folk and Remington, the effect of SOA reported by Theeuwes et al. might only show that the closer the SOA to simultaneity, the stronger the competition. Folk and Remington conducted a study with the use of their cueing paradigm. This time, however, the singleton of the cue display also contained a symbol. Therefore, additionally to a potential spatial validity effect, the authors examined the potential compatibility effect between the symbols within the cue singleton and the subsequent target singleton. As expected by the contingent capture perspective, the symbol compatibility effects were observed only for cues that matched the target color but not for cues of different color than the predefined target. These results provided evidence against the rapid disengagement idea.

Rationale of the Experiment

Folk and Remington (2006) used a compatibility manipulation to test whether spatial attention was captured to the location of the irrelevant singleton at any point in time. Reducing the SOA to below 100 msec, that is, the threshold below which Theeuwes et al. (2000) found additional singleton costs, would not have been decisive as any RT costs may be interpreted both in line with the spatial attention capture stance and in line with the idea of nonspatial filtering costs. Thus, it seems difficult to decide between these alternative interpretations with behavioral measures solely. However, the ERP methodology allows pinpointing particular stages of processing that occur before the end effect of the whole processing stream, that is, before the response. The ERP method may thus be useful in deciding whether attention is first spatially captured to the irrelevant singleton and only then disengaged and reoriented to the less salient target or whether RT costs related to additional singletons are due to a nonspatial competition between irrelevant singleton and the target resulting in delay of attentional deployment to the target (the filtering costs).

The goal of the present study was to examine the potential competition between simultaneously presented irrelevant salient singleton and a less salient relevant target. Although the ERP methodology was already used in the studies of Eimer and Kiss (2008) and Lien et al. (2008) with the aim of investigating the issue of contingent versus pure capture, these studies did not focus on the filtering costs proper. Both Lien et al. and Eimer and Kiss did show evidence for the contingent capture account but could not explain why some authors observed interference effects for irrelevant singletons that did not fall into the attentional set of observers (e.g., Theeuwes et al., 2000; Theeuwes, 1992). To answer this question, one needs to examine the dynamics of attention deployment to the target item in the simultaneous presence of an interfering (more) salient singleton. To this aim, we used a paradigm that combines the logic of an additional singleton with the benefit of spatial manipulations (such as in the cueing paradigms). We created an experimental design that combines a visual search task and a postdisplay probe discrimination task (similar to Wykowska & Schubö, 2010; see also Kim & Cave, 1999; Luck et al., 1993). In the present design, the point of interest was the additional singleton condition, that is, when both singletons were presented simultaneously in the same display. In this case, the singletons directly competed for the deployment of attention. The focus of analysis was the search-locked N2pc, which, as a marker of allocation of spatial attention (e.g., Eimer, 1996), should be informative with respect to whether the irrelevant singleton captured spatial attention or whether attention was successfully allocated to the target. If spatial attention was driven to the irrelevant singleton, a pronounced N2pc for the irrelevant singleton should be observed. On the contrary, if the irrelevant singleton did not capture spatial attention, an N2pc should be observed for the target but not for the irrelevant singleton.

Additional analyses of the postdisplay probes allowed for investigating the development of neural activity to the search display over time (due to two different SOAs) and its impact on subsequent processing of the probe. Early probe-locked ERP components should be sensitive to the probe position manipulation. It has been shown that the P1 component is usually larger for stimuli that are presented at cued locations as compared with ignored locations (e.g., Hillyard, Vogel, & Luck, 1998; Hopfinger & Mangun, 1998). Also in visual search paradigms, the P1 was observed to be more positive for probes presented at relevant (target) positions as compared with irrelevant positions (Wykowska & Schubö, 2010; Luck & Hillyard, 1995; Luck et al., 1993). This is usually interpreted as reflecting a sensory gain control, that is, a mechanism that increases or decreases neural activity related to a given stimulus depending on whether it appears at a previously relevant or ignored location. Therefore, the probe P1 should reflect the neural activity generated by the previously presented search display, with the SOA manipulation indicating the activity development over time.

METHODS

Stimuli and Apparatus

Stimuli were presented on a 17-in. computer screen with a 100-Hz refresh rate placed at a distance of 100 cm from an observer. The items of the search display were positioned on three imaginary circular arrays with diameters of 4.6°, 7.1°, and 9.3° of visual angle on a light-gray background. The outer and middle circles contained eight elements each, and the inner circle contained three elements. There were four possible display types: (1) a target-present display (Figure 1A); (2) an irrelevant color singleton display (Figure 1C); (3) an additional singleton display (a display with the target and the irrelevant singleton; see Figure 1B), and (4) a blank display (Figure 1D).[1] The target (blue outline circle, 0.57° diameter) could appear at one of four positions (upper left/right or lower left/right from the middle point) of the middle circle. The target was embedded in a set of 18 blue outlines of vertical rectangles (0.28° × 0.63° of visual angle)—target-only displays, or in a set of 17 blue rectangular outlines and one red outline—displays with both singletons. Blank trials consisted of a set of 19 blue rectangular outlines, and displays with only the irrelevant singleton consisted of 18 blue and 1 red rectangular outlines. The irrelevant singleton was more salient than the target (see control experiment in Wykowska & Schubö, 2010) and could also appear only at one of the four possible target positions. There was an equal amount of trials (25%) for each search display type. The probe consisted in a thin blue bar (0.28° of visual angle) oriented to the left or to the right (45°). The probe could appear in one of the four possible target positions either in the location previously occupied by the target ("On" target), by the color irrelevant singleton ("On"-irrelevant singleton) or by one of the other neutral distractors (an "Off" position). Participants were seated in a dimly lit, electrically shielded, and sound attenuated chamber with a keyboard and a mouse positioned under their hands.
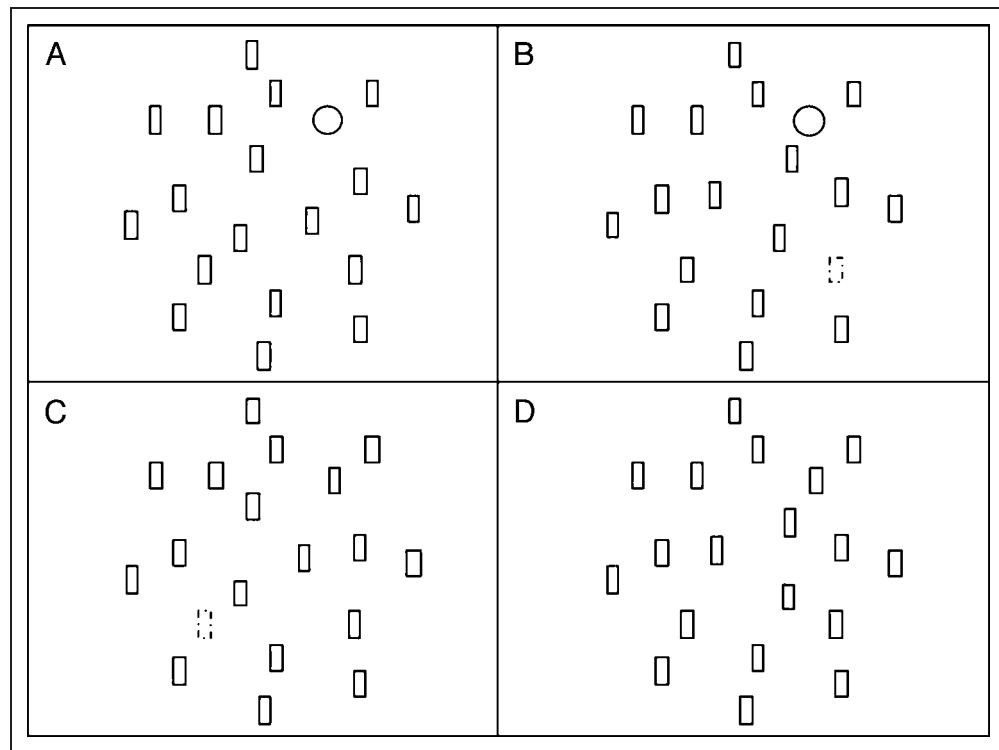
Participants

Fifteen paid volunteers (7 women) aged from 20 to 32 years (mean age = 24.2 years) took part. One participant was left-handed, and all had normal or corrected-to-normal vision. Visual acuity was tested with a Rodenstock R12 vision tester (stimuli 112). The experiment was conducted with the understanding and consent of each participant. None of the observers had taken part in an experiment with such a paradigm before.

Procedure

A trial started with a 400-msec fixation display (one-pixel dot in the center of the screen). Subsequently, the search display was presented for 50 msec followed by a probe (in 75% of trials) with either a short (80 msec) or a long (180 msec) SOA.[2] Blank screen was presented during the

Figure 1. Examples of display types. The upper panels (A and B) show displays containing a predefined target (circle among rectangles): panel A is an example of a target-only display, whereas panel B is an example of a display containing both singletons (the target and the irrelevant color singleton). The lower panels (C and D) show target-absent displays: panel C is an example of a target-absent display that contains an irrelevant singleton, whereas panel D is an example of a blank display. Solid line represents the blue color of the target and the neutral distractors, whereas the dashed line depicts the red color of the irrelevant singleton.

time interval between search display offset and probe onset (30 or 130 msec). In probe-present trials, the probe appeared subsequently for 50 msec. In probe absent trials, blank screen was presented for additional 50 msec. Participants were asked to press the left mouse key positioned under their right hand when the probe was left tilted and the right mouse key when the probe was right tilted. Only after participants responded to the probe detection task, a question concerning the target in the search display appeared on the screen (cf. Figure 2). Observers were to respond to this question with a yes/no response with their left hand by pressing the "4" for target present (upper key) or "0" for target absent (lower key) on the digital part of a keyboard. In case of no probe trials, no response was required in the probe discrimination task. In these trials, after a blank screen presented for 680 msec, a display with question concerning target presence appeared. Participants were asked to respond as fast and as accurately as

Figure 2. Trial sequence. Participants were asked to detect a predefined target (a circle) in a search array. Subsequent to search display presentation, a probe stimulus appeared after a variable SOA. Participants were asked to first respond with one hand to the probe task, that is, discriminate the orientation of the probe, and only then to respond with the other hand to the search task, that is, respond whether there was the target present or not. In case of an incorrect answer either to the probe task or to the search task, a verbal feedback appeared on the screen for 500 msec followed by a 500-msec blank screen.
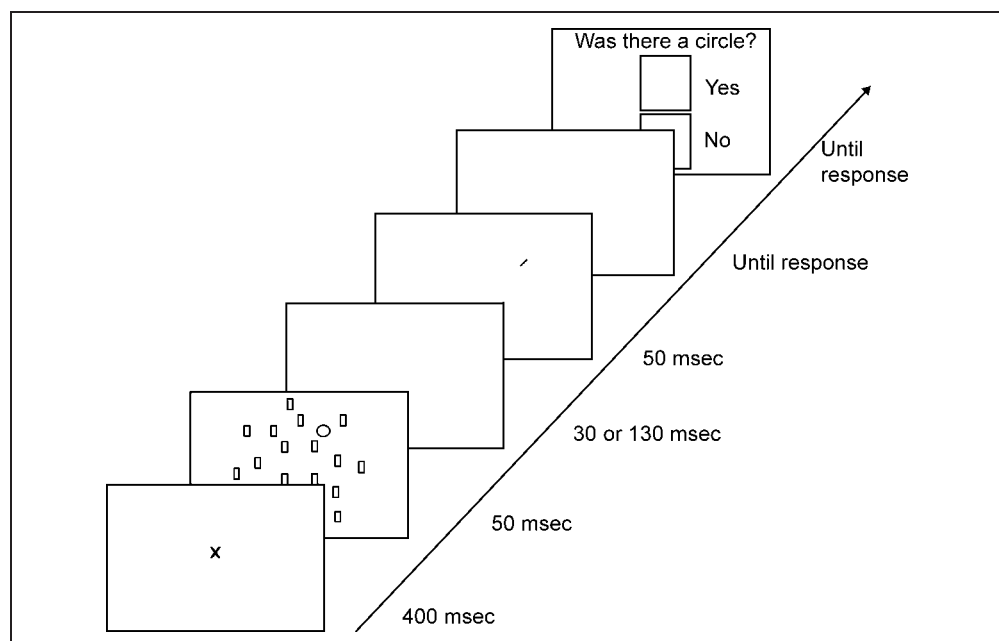
possible in the probe detection task and as accurately as possible in the search task. For visualization of the trial sequence see Figure 2. All conditions were randomly mixed within blocks of 96 trials. The experiment consisted of 3072 experimental trials divided into two parts (16 blocks per part) preceded by two blocks of practice trials. There were 768 trials for each display type, out of which 192 were probe-absent trials. Probe present trials were split into two SOA conditions (336 trials per each SOA condition) and, for displays with both singletons, the number of trials for the "On"-target condition, "On"-irrelevant singleton condition, and "Off" condition was 112 each.

ERP Recording

EEG was recorded with Ag-AgCl electrodes from 37 electrodes (Fp1, Fp2, F3, F4, Fz, F7, F8, F9, F10, FC1, FC2, FC5, FC6, C3, C4, CP1, CP2, CP5, CP6, T7, T8, TP9, TP10, P3, P4, Pz, P7, P8, PO3, PO4, POz, PO7, PO8, O1, O2, Oz, and VEOG). Horizontal and vertical EOG were recorded bipolar from the outer canthi of the eyes and from above and below the observer's left eye, respectively. All electrodes were referenced to Cz and rereferenced off-line to the average of all electrodes. Electrode impedances were kept below 5 kΩ. Sampling rate was 500 Hz with a high cut-off filter of 125 Hz.

Data Analysis

ERP Data

EEG was averaged off-line over 900-msec epoch including a 200-msec prestimulus baseline with epochs time locked to stimulus onset (search display onset or probe onset). Trials with eye movements and blinks on any recording channel (indicated by any absolute voltage difference in a segment exceeding 80 μV or voltage steps between two sampling points exceeding 50 μV) were excluded from analyses. In addition, channels with other artifacts were separately excluded if amplitude exceeded ±80 μV or any voltage was lower than 0.10 μV for a 100-msec interval. Only trials with correct probe and correct search responses were analyzed. Responses occurring below 100 msec and over 1500 msec in the search task or over 1000 msec in the probe task were categorized as errors.

Behavioral Data

Mean RTs and error rates were computed for each participant in both the search and the probe detection task. Before RT analysis in the probe task, errors in any of the two tasks as well as outliers in the probe task were excluded (± 2 SD from mean RT for each participant separately). Before the analysis of the error rates in the probe task, trials with errors and outliers in the search task were excluded.

RESULTS

ERP Results

ERPs Locked to Search Display Onset

First analyses were conducted to investigate how the differences between ERPs evoked by various display types developed over time. These analyses were performed on probe-absent trials. EEG was averaged for the four search display types resulting in four ERP waveforms for each participant and each electrode. A 4×5 ANOVA with the factors Display Type (target vs. irrelevant singleton vs. both vs. blank) and Electrode (O1, O2, Oz, PO7, PO8) was performed for the mean amplitudes of the N1/P2 time window (170–240 msec), N2 time window (240–285 msec), and P3 time window (285–350 msec). Statistics were corrected according to Greenhouse–Geisser when appropriate. The analysis on the mean amplitudes of the N1/P2 time window showed that ERPs elicited by the various display types differed significantly, $F(3, 39) = 7.5, p < .001$. Planned comparisons revealed that only blank trials evoked a more negative mean amplitude ($M = -2.8$ μV, $SEM = 0.7$ μV) compared with other conditions and were significantly different from target trials ($M = -2.2$ μV, $SEM = 0.6$ μV), $F(1, 13) = 9.7, p = .01$, as well as from irrelevant singleton trials ($M = -2.1$ μV, $SEM = 0.7$ μV), $F(1, 13) = 9.8, p = .01$, and additional singleton trials ($M = -1.9$ μV, $SEM = 0.7$ μV), $F(1, 13) = 13.5, p = .005$ (see Figure 3, box to the left). All other comparisons did not reveal any significant differences, all $p > .1$, indicating that at this stage of processing, the brain differentiated only between perfectly homogenous displays (blank trials) and all other types of displays that contained a salient item. Analogous analysis performed for the mean amplitudes obtained in the N2 time window also showed a significant effect for the various search display types, $F(1.6, 22) = 11.7, p < .005$ (see Figure 3, middle box). Planned comparisons revealed that in that later time range, blank trials still elicited a significantly more negative mean amplitude ($M = -1.1$ μV, $SEM = 0.7$ μV) than irrelevant singleton trials ($M = -0.3$ μV, $SEM = 0.7$ μV), $F(1, 13) = 7.4, p = .017$, additional singleton trials ($M = -0.5$ μV, $SEM = 0.7$ μV), $F(1, 13) = 18.5, p = .001$, and target trials ($M = 0.2$ μV, $SEM = 0.7$ μV), $F(1, 13) = 11, p < .01$. This shows that at this stage of processing, the first type of categorization into singleton-absent (blank) trials and singleton-present trials was still present. At the same time, however, in the N2 time window, trials with target displays already differed significantly from irrelevant singleton trials, $F(1, 13) = 4.4, p = .05$, eliciting a more positive amplitude. This indicates that a categorization related to task relevance (target vs. irrelevant) took place at this stage of processing. Target trials were only marginally different from additional singleton trials, $p = .075$ (see Figure 3, middle box), which shows that the categorization of display types according to target presence was almost completed at this stage. Finally, an analysis on the mean amplitudes obtained in the P3 time window showed also a significant effect for the various search display types,

Figure 3. Grand averages of the EEG signal pooled across electrodes O1, O2, Oz, PO7, and PO8, time locked to search display onset. The solid black line represents target displays, the dashed line represents displays with irrelevant singleton, the dotted line reflects displays containing both singletons, and finally, the dashed-dotted line stands for blank displays. The box on the left (light gray) represents the earliest time window analyzed (170–240 msec), the box in the middle (middle gray) depicts the N2 time window (240–285 msec), whereas the box on the right (darkest gray) represents the time window between 285 and 350 msec. Note the high filters cutoff (30 Hz) have been applied to grand averages only for illustration purposes; the statistical analyses were conducted on unfiltered data.
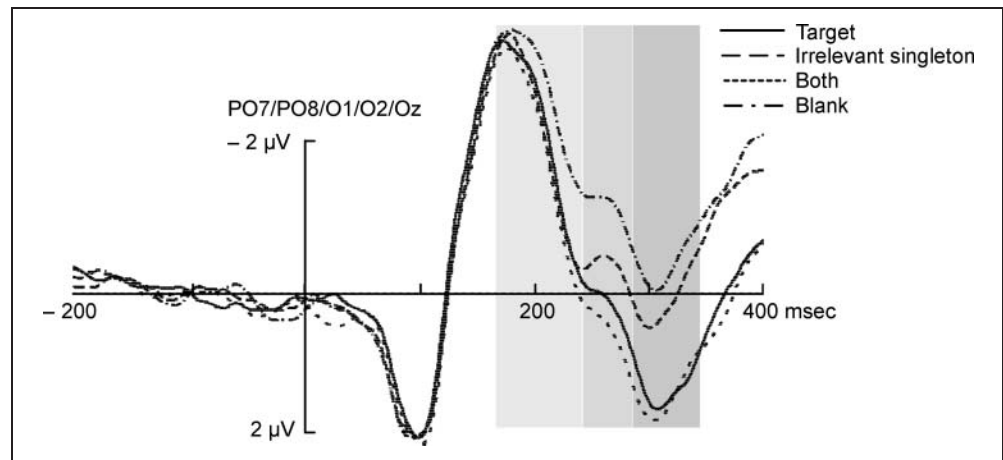
$F(1.3, 17.4) = 11.4, p < .005$ (see Figure 3, right box). Again, trials with target displays elicited a more positive amplitude ($M = 1.1 \ \mu V$, $SEM = 0.6 \ \mu V$) relative to irrelevant singleton trials ($M = -0.04 \ \mu V$, $SEM = 0.6 \ \mu V$), $F(1, 13) = 9, p < .05$, and to blank trials ($M = -0.5 \ \mu V$, $SEM = 0.5 \ \mu V$), $F(1, 13) = 11, p < .01$, but did not differ from additional singleton trials ($M = 1.2 \ \mu V$, $SEM = 0.7 \ \mu V$), $p > .5$, at this stage. The blank trials differed only marginally from irrelevant singleton trials, $p = .077$ (see Figure 3, box to the right), which indicates that at around 300 msec, trial types were already categorized into task-related categories of "target presence" versus "target absence".

N2pc Analyses Time Locked to the Search Display

To investigate the effects on the lateralized N2pc component, we epoched the EEG signal separately for left and right targets/irrelevant singletons for the PO7/PO8 electrode pair resulting in two waveforms (contralateral vs. ipsilateral) for each of the singletons. A repeated measures ANOVA was performed on the N2pc mean amplitudes obtained in the 180- to 300-msec time window with the factors Laterality (contralateral vs. ipsilateral) and Singleton (target vs. irrelevant) for the electrode sites PO7/PO8. The analysis showed that the laterality effect (i.e., the N2pc) was dependent on the type of singleton (target vs. irrelevant) as indicated by the significant Singleton Type × Laterality interaction, $F(1, 13) = 13, p < .005$, see Figure 4. The target evoked more negative amplitudes on the contralateral electrodes ($M = 0.02 \ \mu V$, $SEM = 0.7 \ \mu V$) as compared with the ipsilateral electrodes ($M = 0.7 \ \mu V$, $SEM = 0.7 \ \mu V$; Figure 4A), whereas the irrelevant singleton did not elicit such a difference ($M = 0.5 \ \mu V$, $SEM = 0.7 \ \mu V$ on the contralateral electrodes and $M = 0.2 \ \mu V$, $SEM = 0.7 \ \mu V$ on the ipsilateral electrodes; Figure 4B). Subsequent one-way ANOVAs with the laterality factor (contralateral vs. ipsilateral) conducted for each of the singletons separately confirmed that the effect of laterality was significant for the target, $F(1, 13) = 22$,

$p < .001$, whereas for the irrelevant singleton, the laterality effect was not observed, $p > .1$. Therefore, there was an N2pc for the task-relevant singleton (the target) but not for the irrelevant singleton.

Further analyses were conducted for the additional singleton condition that was split into two categories: both singletons in the same hemifield (see Figure 5, solid line) versus target and irrelevant singleton in opposite hemifields (see Figure 5, dashed line; for a similar procedure, see Wykowska & Schubö, 2010; Hickey et al., 2006). The N2pc was calculated relative to the target item. To compare the two conditions, we calculated difference waves (contralateral–ipsilateral to target presentation). Splitting this condition into the two above categories resulted in two N2pc waves: the N2pc to the target accompanied by additional singleton in the same hemifield and the N2pc to the target accompanied by an additional singleton in the opposite hemifield. Mean amplitudes of the target-related N2pc (180–300 msec) in the additional singleton condition were analyzed with a one-way ANOVA with the factor relative position (same vs. different hemifield). The analyses revealed that the amplitude of N2pc did not differ across the two conditions, $p > .9$, meaning that N2pc was evoked by the target irrespective of whether the irrelevant singleton was in the same or in the opposite hemifield. However, a visual inspection of the grand averages indicated that the two conditions might differ with respect to onset latencies. With the use of the jackknife technique (Miller, Patterson, & Ulrich, 1998) to measure the difference in onset latencies, the statistical significance of that difference was confirmed. The N2pc elicited by the target with the irrelevant singleton in the opposite hemifield had a later onset ($\Delta M = 24$ msec, $SEM = 8$ msec) as compared with the condition when the irrelevant singleton was presented in the same hemifield, $t(13) = 2.94, p < .05$. This suggests that the deployment of spatial attention to the hemifield containing the target was delayed when the irrelevant singleton was presented in the opposite hemifield.

Figure 4. Grand averages of the EEG signal for PO7/PO8 electrode sites time locked to search display onset (additional singleton condition) measured contralateral (dashed line) or ipsilateral (solid line) to (A) the target and (B) the irrelevant singleton. The rectangular area (A) represents the N2pc time window (180–300 msec) in which the laterality factor was statistically significant. High cutoff filters (30 Hz) have been applied to grand averages only for illustration purposes; the statistical analyses were conducted on unfiltered data.
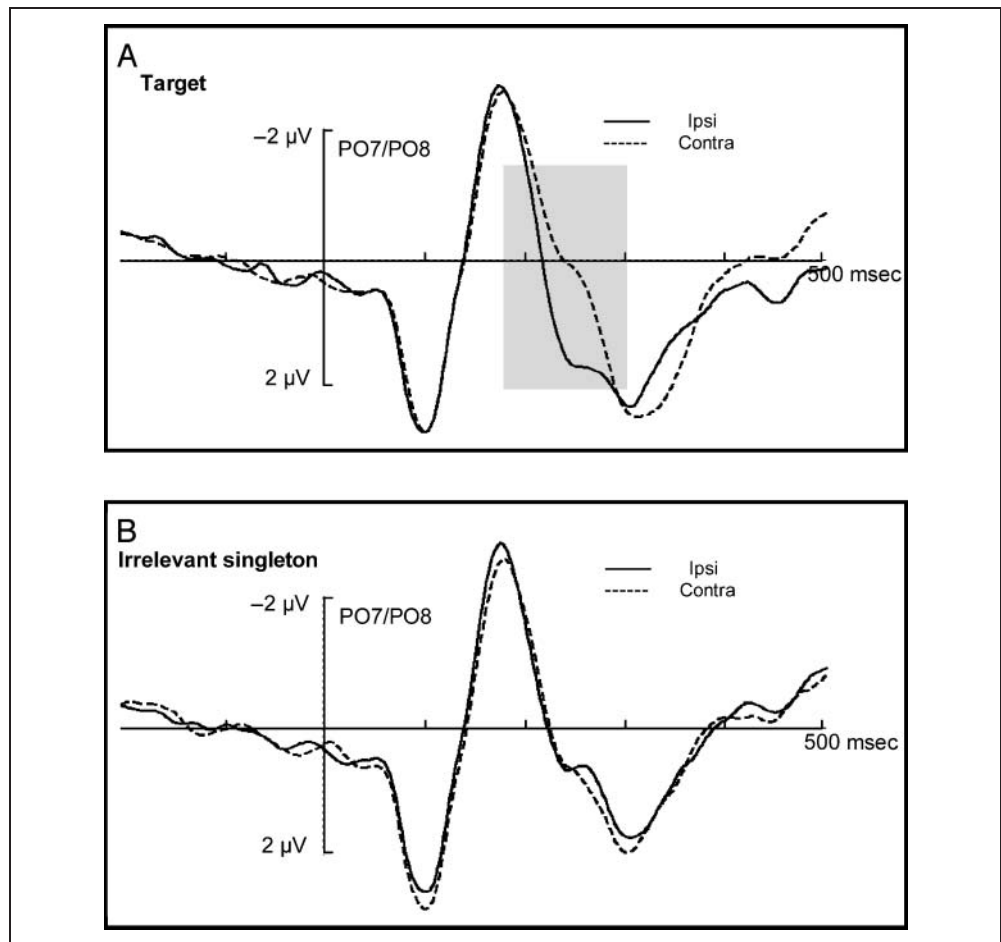
Additional analysis on the mean amplitude values in the N2pc time window also for PO7/PO8 electrodes was conducted for one-singleton displays. An ANOVA with the factors laterality (contralateral vs. ipsilateral) and singleton (target vs. irrelevant singleton) showed similar interaction of singleton and laterality as in the case of additional singleton condition, $F(1, 13) = 23, p < .001$. Also in case of the one-singleton condition, an N2pc was evoked by targets and not by the irrelevant singletons. Mean amplitudes and statistics for this condition are presented in Table 1.

ERPs Locked to Probe Onset

These analyses were conducted on probe-present trials with ERPs time locked to the probe onset. Left- and right-tilted probes were averaged together. Probe-absent trials were subtracted from probe-present trials, which allowed for elimination of overlapping potentials related to search display presentation and for the extraction of potentials related to probe presentation. The subtraction was conducted on epoched data, separately for each search display

Figure 5. Grand averages of the difference waves between the contralateral and the ipsilateral electrode sites (PO7/PO8) measured relative to the target (additional singleton condition) depending on whether the irrelevant singleton was in the same hemifield (solid line) or in the opposite hemifield (dashed line). The dotted line depicts the difference wave for the irrelevant singleton averaged across both conditions (same and opposite hemifield as the target). The gray rectangular area represents the N2pc time window (180–300 msec). High cutoff filters (30 Hz) have been applied to grand averages only for illustration purposes; the statistical analyses were conducted on unfiltered data.
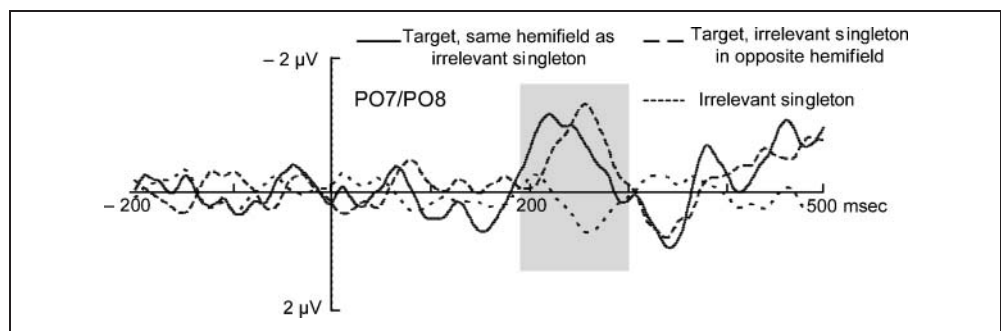
Table 1. Mean (*SE*) Amplitudes of the Contralateral and Ipsilateral Sites (PO7/PO8) to the Target and Irrelevant Singleton within the N2pc Time Window (180–300 msec) for One-singleton Displays

Singleton	Mean (SE) Amplitudes (µV)			
	Contralateral	*Ipsilateral*	*F(1, 13)*	*p*
Target	−0.4 (.7)	0.7 (.7)	32.6	<.001
Irrelevant singleton	−0.36 (.8)	−0.25 (.8)	0.9	>.3

type and each SOA, time locked to probe onset. The EEG signal was averaged for the additional singleton condition for three probe positions ("On"-target, "On"-irrelevant singleton, and "Off") and two SOAs. In this way, six ERP waveforms were obtained for each participant and each electrode. A 3 × 5 ANOVA with the factors of position ("On"-target vs. "On"-irrelevant singleton vs. "Off") and electrode (O1, O2, Oz, PO7, PO8) was conducted for mean amplitudes of probe-locked ERPs in the P1 time window in the additional singleton condition for the short and long SOA conditions separately. Statistics were corrected according to Greenhouse–Geisser when appropriate. In the short SOA condition, analysis on the P1 component in the 130- to 220-msec time window revealed a position effect,

$F(2, 26) = 9.8, p < .001$ (Figure 6A, left), showing a slightly positive amplitude for the target position ($M = 0.4$ µV, $SEM = 0.2$ µV; Figure 6A, left, solid line) but not for the irrelevant singleton position ($M = -0.24$ µV, $SEM = 0.2$ µV; Figure 6A, left, dashed line) or the "Off" position ($M = -0.22$ µV, $SEM = 0.2$ µV; Figure 6A, left, dotted line), $F(2, 26) = 4.7, p < .05$. Planned comparisons revealed that the mean amplitude of the waveform was significantly more positive at the target position relative to the irrelevant singleton, $F(1, 13) = 8, p < .05$, and the "Off" position, $F(1, 13) = 4.7, p < .05$. The position of the irrelevant singleton did not differ from the "Off" position, $p > .9$. The long SOA condition elicited similar P1 effects in an earlier time window (100–180 msec; Figure 6A, right). The mean amplitude of the waveform in that time window differed significantly, $F(2, 26) = 9.8, p < .005$, depending on whether the probe was presented at the previous target position ($M = 1.0$ µV, $SEM = 0.3$ µV; Figure 6A, right, solid line), the irrelevant singleton's position ($M = 0.3$ µV, $SEM = 0.2$ µV; Figure 6A, right, dashed line), and the "Off" position ($M = -0.1$ µV, $SEM = 0.2$ µV; Figure 6A, right, dotted line). Probes presented at the "On"-target position elicited significantly more positive P1 amplitude than probes presented at the "On"-irrelevant singleton position, $F(1, 13) = 5, p < .05$, or "Off" position, $F(1, 13) = 17, p < .005$. Also the difference between the "On"-irrelevant singleton position and the "Off" position

Figure 6. Grand averages of the EEG signal pooled across O1, O2, Oz, PO7, and PO8 electrodes locked to probe onsets for probes following displays with both singletons. The gray rectangular areas depict the P1 time window subject to statistical analyses (130–220 msec for short SOA and 100–180 msec for long SOA). (A) ERPs to probes in the short SOA condition (left) and long SOA condition (right) with respect to probe positions: On-target (solid line), On-irrelevant singleton (dashed line), and "Off" (dotted line); (B) ERPs to probes presented on target positions (left) and on irrelevant singleton positions (right) for long SOA depending on whether the two singletons were in the same hemifield (solid line) or opposite hemifields (dashed line). Note that the baseline started 200 msec before probe presentation onset and that the statistical analysis was conducted on unfiltered data. High cutoff (30 Hz) filters have been applied to grand averages only for illustration purposes.
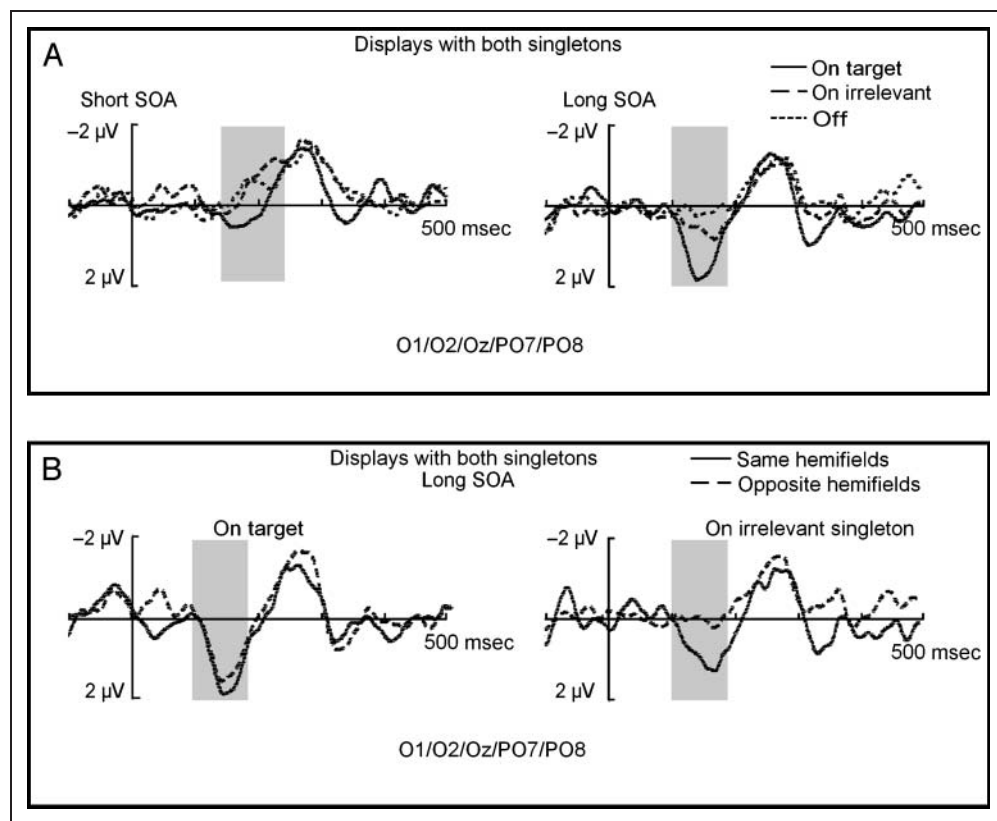
reached the level of significance, $F(1, 13) = 5.8, p < .05$. To investigate whether the difference between the irrelevant singleton position and the "Off" position in the long SOA condition was due to the irrelevant singleton itself or rather was related to the target presented in the vicinity, we split the additional singleton trials into same hemifield and opposite hemifield conditions in an analogous way as for N2pc analysis. A 4×5 ANOVA was conducted on mean P1 amplitudes for long SOA (100–180 msec) with the factors relative position (On target, same hemifield; On target, opposite hemifield; On irrelevant, same hemifield; and On irrelevant opposite hemifield) and electrode (O1, O2, Oz, PO7, PO8). Statistics were corrected according to Greenhouse–Geisser when appropriate. The analysis revealed a significant effect of relative position, $F(3, 39) = 3.2, p < .05$ (Figure 6B). Planned comparisons showed that the mean amplitude of P1 for probes presented at the target location did not differ with respect to where the irrelevant singleton was presented relative to the target (same hemifield: $M = 1.2$ µV, $SEM = 0.3$ µV, vs. opposite hemifield, $M = 0.9$ µV, $SEM = 0.4$ µV; Figure 6B, left), $p > .47$. In both conditions, probes evoked a significant P1 positivity: one-sample t test against zero, $t(13) = 2.6, p < .05$ for the opposite hemifield condition; $t(13) = 4.6, p < .001$ for the same hemifield condition. When probes appeared at the position of the irrelevant singleton and the target was in the opposite hemifield (Figure 6B, right, dashed line), the P1 positivity was not observed ($M = 0.07$ µV, $SEM = 0.3$ µV), one-sample t test against zero, $p > .8$, that differed, $F(1, 13) = 4.1, p = .06$, from the mean amplitude in the condition in which the target was presented in the same hemifield ($M = 0.8$ µV, $SEM = 0.4$ µV), one-sample t test against zero, $t(13) = 2.2, p < .05$ (Figure 6B, right, solid line). These results suggest that the difference in P1 amplitude elicited by probes presented at the previous location of the irrelevant singleton as compared with neutral locations was not due to the irrelevant singleton itself but rather the presence of the target in its vicinity. Results of the analogous analysis as well as exact mean amplitude values for the short SOA condition (130–220 msec) are presented in Table 2.

Taken together, the results of probe-locked P1 in the additional singleton condition indicate some differential

Table 2. Mean (*SE*) Amplitudes within the P1 Time Window Time Locked to Probe Onset in Short SOA Condition as a Function of Relative Position of Singletons (Same Hemifield vs. Opposite Hemifield) and Singleton Type (Target vs. Irrelevant) in the Additional Singleton Condition

| Singleton | Mean (SE) Amplitudes (µV) | | | |
	Same Hemifield	Opposite Hemifields	F(1, 13)	p
Short SOA (130–220 msec)				
Target	0.01 (.3)	0.6 (.3)	1.9	>.18
Irrelevant	−0.07 (.5)	−0.2 (.1)	0.12	>.7

Table 3. Mean (*SE*) Amplitudes within the P1 Time Window Time Locked to Probe Onset in Short SOA Condition and Long SOA Condition as a Function of Position ("On" vs. "Off") and Singleton Type (Target vs. Irrelevant) for One-singleton Displays

| Singleton | Mean (SE) Amplitudes (µV) | | | |
	On	Off	F(1, 13)	p
Short SOA (130–220 msec)				
Target	0.8 (.3)	−0.1 (.2)	13.3	<.005
Irrelevant	0.8 (.2)	0.2 (.2)	9.8	<.01
Long SOA (100–180 msec)				
Target	2.5 (.6)	1.5 (.5)	12.8	<.005
Irrelevant	0.5 (.5)	0.3 (.4)	1.4	>.25

pattern of neuronal activity for probes presented at a previous target location relative to neutral locations. Interestingly, this pattern was observed briefly after display presentation, that is, already at the short SOA. No such effect was observed for the location of the irrelevant singleton in either of the SOAs.

Additional analyses were conducted for the one-singleton condition with regard to two probe positions ("On," that is, the previous position of a singleton vs. "Off," i.e., the previous position of a neutral distractor) and two SOAs (short vs. long). These analyses showed that in case of the one-singleton condition, at the short SOA, both target location and irrelevant singleton's location resulted in enhanced processing of the subsequently presented probe. In the long SOA condition, this effect was observed only for the target and not for the irrelevant singleton. Mean amplitudes and statistics for the P1 component for displays containing only one singleton are presented in Table 3.

Behavioral Data

Reaction Times in the Probe Task

Behavioral analyses also focused on the additional singleton condition. Individual mean RTs for probe-present trials (left- and right-tilted averaged together) were split into the "On-Target," "On-Irrelevant," and "Off" conditions and two SOAs for the additional singleton condition. A 3×2 ANOVA with the factors SOA (short vs. long) and position ("On"-target vs. "On"-irrelevant singleton vs. "Off") revealed a significant effect of position, $F(2, 26) = 26, p < .001$, showing fastest RTs to the probes presented at the target position ($M = 442$ msec, $SEM = 16$ msec), then at the irrelevant singleton ($M = 460$ msec, $SEM = 17$ msec) and longest when presented at the "Off" position ($M = 466$ msec, $SEM = 16$ msec) (see Figure 7A and B). A significant effect of SOA, $F(1, 13) = 37, p < .001$, indicated faster RTs for
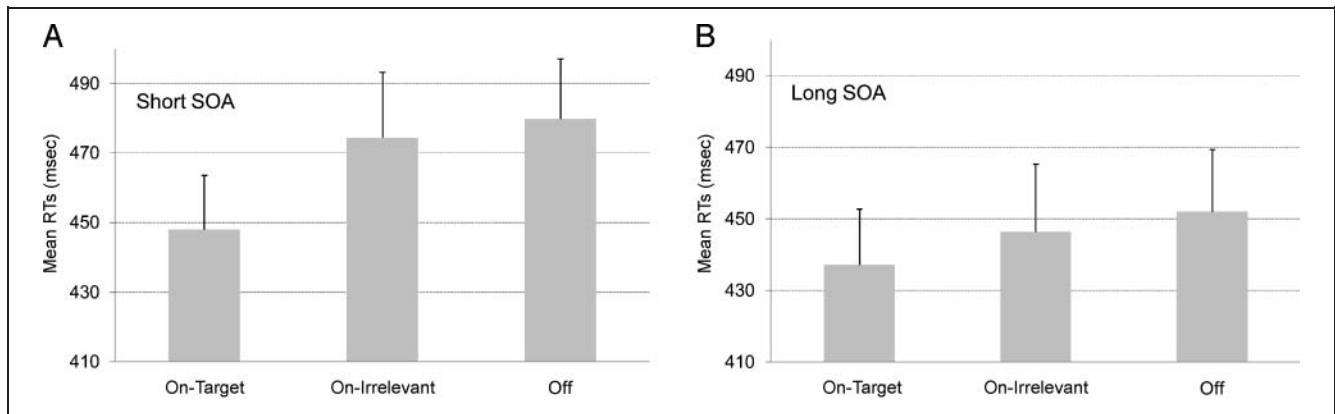
Figure 7. Mean RTs in the probe discrimination task for probes following displays with both singletons with short SOA (A) or long SOA (B) as a function of probe position (On-target vs. On-irrelevant singleton vs. "Off"). Error bars represent *SEM*s.

long SOAs ($M = 445$ msec, *SEM* = 15 msec) compared with short SOAs ($M = 467$ msec, *SEM* = 17 msec). As there was also a position × SOA interaction, $F(2, 26) = 3.7, p < .05$, further analyses were conducted for short and long SOA conditions separately.

In the short SOA condition, the effect of position reached the level of significance, $F(1.4, 18.5) = 37, p < .001$, revealing that the "On"-target position yielded shortest RTs ($M = 448$ msec, *SEM* = 16 msec), followed by the "On"-irrelevant singleton position ($M = 474$ msec, *SEM* = 19 msec) and the "Off" position ($M = 479$ msec, *SEM* = 17 msec) (see Figure 7A). The "On"-target position differed significantly from both the "On"-irrelevant condition, $F(1, 13) = 20, p < .005$, and the "Off" condition, $F(1, 13) = 19.5$, $p < .005$. The "On"-irrelevant singleton position did not yield different RTs than the "Off" position, $p > .18$. In the long SOA condition, the main effect of position was only marginally significant, $F(2, 26) = 2.9, p = .074$. Planned comparisons revealed similar effects to the short SOA condition: the "On"-target position ($M = 437$ msec, *SEM* = 16 msec) differed significantly from both the "On"-irrelevant position ($M = 446$ msec, *SEM* = 15 msec), $F(1, 13) = 6.5$, $p < .05$, and the "Off" position ($M = 448$ msec, *SEM* = 15 msec), $F(1, 13) = 5.3, p < .05$. The "On"-irrelevant singleton position again did not yield different RTs than the "Off" position, $p > .7$ (see Figure 7B). These results parallel probe-locked ERP effects, indicating prioritized processing of probes presented at the location of the target but not of the irrelevant singleton.

Error Rates in the Probe Task

Analogously to the analyses on RTs, individual mean error rates for probe-present trials (left- and right-tilted averaged together) were split into the "On-Target," "On-Irrelevant," and "Off" conditions and two SOAs for the additional singleton condition. The analysis of error rates showed similar results as RTs (cf. Figure 8). A main effect of position was observed, $F(2, 26) = 3.6, p < .05$, indicating lowest

error rates for probes presented at the target position ($M = 5\%$, *SEM* = 1%), then the irrelevant singleton position ($M = 6.2\%$, *SEM* = 1%), and highest for the "Off" position ($M = 7\%$, *SEM* = 1%). Planned comparisons showed that the target position differed significantly from the "Off" position, $F(1, 13) = 4.7, p < .05$, whereas the irrelevant singleton position did not, $p > .2$. This parallels probe-locked ERP results and RT data in that it indicates facilitated processing of probes presented at target locations but not at irrelevant singleton locations. The position effect did not interact with the SOA factor $p > .1$.

Analogously to the analyses on the ERPs, additional analyses were conducted on the RTs and error rates in the one-singleton condition with respect to "On"-singleton and "Off" positions and SOA. Similarly to the results of the probe-locked P1 component in the one-singleton condition, the behavioral results showed a transient benefit for probes at positions of both singletons at the short SOA, which remains observed for the target and disappears for the irrelevant singleton at the longer SOA. Results of these analyses (mean RTs and mean error rates as well as statistics) are presented in Table 4.
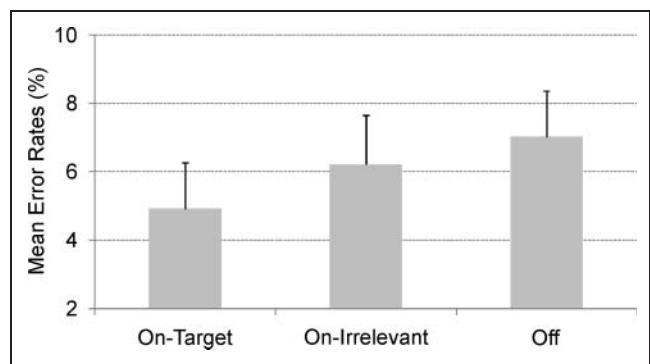

Figure 8. Mean error rates in the probe discrimination task for probes following displays with both singletons as a function of probe position (On-target vs. On-irrelevant singleton vs. "Off"). Error bars represent *SEM*s.

Table 4. Mean (*SE*) RTs and Error Rates as a Function of SOA, Position ("On" vs. "Off"), and Singleton Type (Target vs. Irrelevant) for One-singleton Displays

Singleton	On	Off	F(1, 13)	p
Mean (SE) RTs (msec)				
Short SOA				
Target	449 (15)	476 (18)	22.5	<.001
Irrelevant	450 (14)	466 (15)	13	<.005
Long SOA				
Target	442 (15)	452 (17)	6.5	<.05
Irrelevant	446 (15)	450 (16)	1.1	>.3
Mean (SE) Error Rates (%)				
Short SOA				
Target	4.4 (1.2)	7.3 (1.4)	8.25	<.05
Irrelevant	5.3 (1.3)	6.4 (1.5)	3.5	.083
Long SOA				
Target	5.9 (1.2)	7.2 (1.2)	1.7	>.2
Irrelevant	5.5 (.8)	6.4 (1.2)	1.7	>.2

Error Rates in the Search Task

The one-way ANOVA with the factor display type (target vs. irrelevant singleton vs. both vs. blank) conducted on error rates in the search task showed that error rates in these four conditions did not differ significantly, $p > .3$ (target: $M = 4.5\%$, $SEM = 1.3\%$; irrelevant singleton: $M = 3.5\%$, $SEM = 1.1\%$; both singletons: $M = 5.4\%$, $SEM = 1.2\%$; blank displays: $M = 4.3\%$, $SEM = 1.3\%$).

DISCUSSION

The present experiment was designed to investigate the competition between two salient items presented simultaneously, one being a task-relevant target and the other being a more salient but irrelevant singleton. The question of interest was concerned with the nature of the influence such an irrelevant singleton might have on target processing: does the additional singleton, being the most salient item in the visual field, capture spatial attention that has to be later redirected to the target, or does the singleton cause nonspatial filtering costs and thereby simply delays the deployment of spatial attention to the task-relevant target?

First analyses were conducted on ERPs locked to the search display in probe-absent trials. These analyses were performed to examine how the differences among ERPs evoked by various display types developed over time. Results showed that first, within the 170- to 240-msec time window, only the blank displays differed from the other

three types of displays. Subsequently, and already after 240 msec, additionally to the remaining difference between blank trials and other types of trials, the irrelevant singleton displays began to differentiate from target displays. Finally, in the time window of P3 (285–350 msec), the displays were clearly sorted into two categories: target-present displays (target-only displays as well as displays with both singletons) and target-absent displays (irrelevant singleton displays and blank trials). Such dynamics are in line with previous findings (Wykowska & Schubö, 2010; Schubö, Wykowska, & Müller, 2007). The first observed difference between blank trials and all three other display types suggests that the brain first rejects the easiest case of perfectly homogeneous blank trials based, most probably, on global processing of blank displays as whole units (Schubö et al., 2007; Duncan & Humphreys, 1989). Subsequently, at around 240 msec, the brain is able to successfully discriminate not only blank displays from other types of displays but also targets from irrelevant singletons although both are salient. Finally, at around 350 msec, the ERP waveform elicited by the irrelevant singleton trials start converging with the ERP waveform elicited by the blank trials which shows that at this stage the four types of displays are being sorted into two categories (target absent vs. present). This should allow for correct responses according to the task.

Search-locked N2pc: Irrelevant Singletons Do Not Capture Spatial Attention but May Produce Filtering Costs

The analyses of interest focused on the N2pc, which is an ERP marker of allocation of spatial attention to display items (e.g., Woodman & Luck, 2003; Eimer, 1996). In the present study, the N2pc has been measured relative to the target and to the irrelevant singleton for the additional singleton condition. If spatial attention was captured by the irrelevant singleton, then a pronounced N2pc related to the irrelevant singleton should be observed. Results showed that the target evoked a significant N2pc (Figure 4A), whereas the irrelevant singleton did not (Figure 4B), providing clear evidence that at the time when the N2pc was observed (after 180 msec poststimulus), attention was successfully allocated to the target. A more detailed examination of the additional singleton condition was based on creating two subconditions: singletons in the same hemifield versus singletons in opposite hemifields. N2pc was calculated relative to the target. If attention was first allocated to the irrelevant singleton and only then redirected to the target (attentional capture perspective), then one should observe an N2pc of reversed polarity for trials where the distractor singletons were presented in the hemifield opposite to the target (Wykowska & Schubö, 2010; Hickey et al., 2006). This was clearly not the case. Instead, results showed no difference in target-related N2pc amplitudes with respect to the singleton distractor (Figure 5, solid and dashed lines). This suggests that attention was successfully allocated to

the target regardless where the irrelevant singleton was positioned. Interestingly, although the mean amplitudes of the N2pc did not differ across these two subconditions, the onset latency of the N2pc difference wave was earlier when both singletons were presented in the same hemifield as compared with the opposite hemifields. This might indicate that the deployment of attention to the hemifield containing the target was somewhat delayed when the irrelevant singleton was presented in the opposite hemifield, suggesting that the irrelevant singleton did compete with the target for the allocation of attention. This competition must have been taking place before the allocation of spatial attention as spatial attention was found not to be allocated to the irrelevant singleton. The competition might, therefore, have been of a nonspatial sort resulting in some influence of the irrelevant singleton on the deployment of attention to the target. This interpretation fits to the idea of the filtering costs brought forward by Folk and Remington (2006). According to the authors, filtering costs might explain performance costs found in additional singleton paradigms (e.g., Theeuwes et al., 2000; Theeuwes, 1992) without the need of assuming capture of spatial attention. The authors argue that an additional irrelevant singleton might interfere with the deployment of attention to the target even if it does not share characteristics with the target. The interference/competition being nonspatial in nature does not however imply that attention is first allocated to the irrelevant singleton and only then reoriented to the target.

Probe-locked P1: Sensory Gain for Probes at the Target Position

Probe-locked ERPs allow for investigating how neural activity for targets and/or irrelevant singletons developed over time affecting processing of subsequently presented stimuli. The P1 component has been observed to be modulated in post (search) display probe paradigms (or cueing paradigms) already in earlier studies (e.g., Wykowska & Schubö, 2010; Hillyard et al., 1998; Hopfinger & Mangun, 1998; Luck et al., 1993). Hillyard et al. (1998), Luck and Hillyard (1995), Luck et al. (1993) observed a larger P1 positivity for probes presented at target positions as compared with irrelevant singleton positions. The authors argue that P1 reflects a sensory gain control mechanism that enhances/ suppresses neural activation at relevant or ignored locations, respectively. Therefore, because in the present design the target was not only salient but also relevant, it must have elicited a high peak of neural activity. This should result in a sensory gain observed for the target and/or a reduced gain for the irrelevant singleton.

The present results showed enhanced positivity in the P1 range for probes presented at the target position relative to other positions in the short SOA condition (Figure 6A, left, solid line). No such effect was observed for the irrelevant singleton (Figure 6A, left, dashed line). The long SOA condition also revealed larger P1 positivity for probes presented

at the target position as compared with the "Off" condition (Figure 6A, right, solid line).[3] Interestingly, also probes at the position of irrelevant singleton showed a similar, although smaller effect (Figure 6A, right, dashed line). As it turned out, this effect was not due to the irrelevant singleton itself but to the condition when the target was presented in the same hemifield as the irrelevant singleton. This conclusion can be drawn from the analyses on P1 mean amplitudes for the additional singleton condition at the long SOA with the subconditions of target plus irrelevant singleton in the same hemifield versus opposite hemifields. These analyses showed that the P1 amplitude for probes presented at irrelevant singleton positions depended strongly on whether the target was presented in the same hemifield or in the opposite hemifield. In the first case, significant P1 positivity was observed (see Figure 6B, right, solid line), whereas no such positivity was observed when the target was presented in the opposite hemifield (see Figure 6B, right, dashed line). This result suggests that probes presented at an irrelevant singleton position in the vicinity of the target also received some sensory gain, probably due to that fact that the irrelevant singleton has fallen within the attention focus (directed to the target) that might have been broad enough to embrace also the irrelevant singleton in its span.

Analyses of behavioral data for the additional singleton condition supported the probe-locked ERP effects: RTs to probes at target positions were faster as compared with other positions in both SOA conditions and no clear sign of analogous benefit of the irrelevant singleton's position was observed (cf. Figure 7). Error rates followed a similar pattern (cf. Figure 8).

Taken together, the effects on probe-locked P1, supported by behavioral data, showed sensory gain for probes presented at target locations that were not only salient but also relevant. No clear sign of a sensory gain for probes appearing at the irrelevant salient location was observed. This is well in line with previous findings and suggests that items that are not only salient but also relevant elicit the highest level of neural activity among all items presented in the visual field. These results, that is, larger activity at previous target locations compared with neutral locations and no such enhancement for the irrelevant singleton locations at both SOAs, imply that the level of neural activity related to the target which was not only salient but also relevant must have been enhanced.[4]

When Irrelevant Singletons Are the Only Salient Items in the Visual Field

The present N2pc results clearly showed that when two singletons were presented simultaneously, one of them being more salient but irrelevant and the other (the target) being less salient and task relevant, the irrelevant singleton did not capture spatial attention. Instead, it might have produced filtering costs and a delayed deployment of attention to the target in the situation of direct competition

(i.e., when the singletons were presented in opposite hemifields). Do similar effects occur in the one-singleton displays? Interestingly, also in these conditions, an N2pc was observed for targets but not for irrelevant singletons (see Table 1). This suggests that even in these trials, due to top–down control, attention was not captured by the irrelevant singleton. At the same time, though, the probe-locked P1 at short SOA was more enhanced for probes presented at the position of the target and the irrelevant singleton (as compared with neutral positions; see Table 3). Although the P1 amplitude related to the irrelevant singleton was smaller than the P1 amplitude related to the target, it was still more positive as compared with the P1 evoked by probes presented at neutral positions. Analogous results were found in the RT data and error rates (see Table 4). These results might indicate that there was some sensory gain for probes presented at irrelevant singleton positions when these singletons were the only salient items in the visual field. It is important to note that there was no evidence for the allocation of spatial attention to the irrelevant singleton in this condition as no N2pc was observed for the irrelevant singletons.[5] Instead, it might be the case that neural activity was transiently more enhanced for all locations where a conspicuous item was presented—irrespective of their relevance. This might have resulted in an enhanced activity for probes presented at the same location as the singletons. No such gain was observed in the long SOA condition suggesting that with time, the neural activity related to the conspicuous irrelevant locations might have been suppressed or simply died out. Importantly, also no gain for the irrelevant singleton position was observed when the target was presented in the same display (the additional singleton condition) even at the short SOA. This suggests that when two locations elicited enhanced neural activity and one of them was task relevant, the other location might have been immediately suppressed resulting in no sensory gain for subsequent stimuli presented at that location.

Top–Down Mechanism Prevents Attentional Capture

Because the present results showed no evidence for attentional capture to irrelevant singletons, any observed influence of irrelevant singletons on processing of the target might be due to nonspatial filtering costs (see also, e.g., Folk & Remington, 2006). It is important to note that the present experimental design aimed at encouraging participants to create an attentional set for a predefined target. This has been induced through task instructions and through introducing four display types that made it difficult to select the target based solely on its saliency signal. Under these circumstances was the top–down selection mechanism capable of controlling bottom–up processing so that the most salient item did not capture attention but, instead, attention was allocated to the task-relevant target (for similar results, see also Wykowska & Schubö, 2010; Eimer & Kiss, 2008; Folk & Remington, 2006). That does not imply that attention cannot be driven to salient items in a bottom–up manner under other circumstances. When the most salient item would also be the relevant target or when participants would be encouraged to apply a more bottom–up strategy to complete the task, such as, for example, the singleton-detection search mode (Bacon & Egeth, 1994), it is likely that attention would be driven to items in the visual field based solely on their salience signals. However, the present data show that the salience-based selection mechanism in attention guidance is penetrable to top–down control given that an appropriate attentional set has been established.

These results cast a light on how the brain deals with the abundance of input it receives. It is clear that salient information, even when not relevant to the task at hand, is still processed at the early stages because of the neuronal response it evokes (e.g., Chelazzi, Duncan, Miller, & Desimone, 1998; Hopfinger & Mangun, 1998). For subsequent higher level stages of processing, the brain needs to filter irrelevant information. Spatial attention is one way of doing so. Equipped with such a mechanism, the brain is capable of focusing only on locations in which important and relevant stimuli occur at a given time. As observed in the present data, neural activity related to the irrelevant salient item is filtered out as spatial attention is allocated to the task-relevant location of the target. At the same time, however, the salience-related neuronal response to the irrelevant singleton is temporarily present and might delay deployment of attention to the location of the relevant item. This might have important consequences for natural human actions. As selection mechanisms are there to optimize human interaction with the environment (see, e.g., the selection—for action view of Allport, 1987; or perspectives postulating close coupling between action and perception, such as the premotor theory of attention by Rizzolatti, Riggio, & Sheliga, 1994; or the Theory of Event Coding by Hommel, Müsseler, Aschersleben, & Prinz, 2001) and because of the fact that attention is strongly coupled with eye movements (e.g., Deubel & Schneider, 1996), the present results imply the following: in a natural scenario of, for example, a football match, a player is to follow the ball to be ready to receive it when it is passed in his direction. His gaze should be efficiently following the ball even if the referee wearing a bright red T-shirt runs into the player's visual field (the player's attention should be efficiently focused on the ball irrespective of the interfering stimulus in the surrounding). At the same time, however, one should be aware that although the player's attention is focused on the ball, some temporal delays in the player's reaction to the approaching ball might occur as the player's brain needs to filter out the interfering neuronal response to the salient additional information.

Theoretical Framework

The present results might be interpreted within the framework of classical models of visual search such as

the Guided Search (Wolfe et al., 2003; Wolfe, 1994; see also the FeatureGate model by Cave, 1999; or the Dimensional Weighting account by Found & Müller, 1996). In these models, it is assumed that the visual scene is coded in spatially arranged dimension-specific maps such as "color" or "orientation." For example, a pop-out color item is represented as a salience signal in the color map retaining spatial organization. The dimension-specific maps feed into a master map of activation, which we will call a priority map (Yantis & Jones, 1991). Weighted salience signals from the dimension-specific maps are summed at the priority-map level, and attention is subsequently guided to the location with the highest activation peak. Weighting of dimensions can take place in a top–down manner through, for example, task instructions or cueing (Wykowska & Schubö, 2010; Müller et al., 2003; Wolfe, 1994). On the basis of the present results, we argue that in the additional singleton condition, the priority map was, for a short time, containing two locations with higher activation peaks. One was related to the target and the other to the irrelevant singleton. Because the results showed that attention was allocated to the target and not to the irrelevant singleton and because the target was of a lower level of saliency (see the control experiment in Wykowska & Schubö, 2010), it must have been top–down weighting that outweighed the activation related to the irrelevant singleton's saliency signal. The weighting of the signal must have resulted in a higher peak for the target, which, in turn, guided attention to the target location. However, the presence of an additional peak of activation for the irrelevant singleton delayed the allocation of attention to the target location. This may have been due to a competition between the two activation peaks at the priority map: it may have taken time before the two activation peaks clearly differed to guide attention to the highest activation peak. It is important to note that the temporal delay of attention deployment to the target does not imply that attention was allocated to the irrelevant singleton at any time.

In summary, the present ERP study showed that irrelevant singletons do not capture spatial attention when participants are set for detecting a target of a predefined dimension. An ERP marker of spatial attention, namely, the N2pc, was observed for the target but not for the irrelevant singleton. At the same time, the onset of N2pc for the target was delayed when the irrelevant singleton was presented in the opposite hemifield than the target as compared with the same hemifield condition. This suggests that the irrelevant singleton had some impact on processing of the target. However, its impact was nonspatial in nature as attention was still successfully allocated to the target. This is in line with the idea of filtering costs produced by additional, irrelevant singletons. Such singletons may elicit enhanced neural activity because of their salience, which might result in some interference and delay in the deployment of spatial attention to the relevant target item. However, this interference does not imply capture of spatial attention. In other words, when partici-

pants search for predefined targets, additional irrelevant singletons may be processed to some extent but need not attract attention.

Notes

1. Note that although the condition of interest was the additional singleton condition (both singletons in the same display), the other three display conditions were introduced for a balanced design and equal probabilities of (1) the target appearing alone, (2) with the irrelevant singleton, (3) the irrelevant singleton alone, and (4) no singletons at all. The design also enabled an equal amount of positive responses (displays containing targets alone as well as displays with both singletons) and negative responses to target detection (irrelevant singleton displays as well as blank displays). Moreover, the four display types encouraged a top–down strategy of target selection and attentional set for the target-defining feature. Because the displays containing only the irrelevant singleton had to be distinguished from target-only displays, participants were encouraged to set their attention to the target feature and not to select the target based solely on saliency signals (i.e., "detect any salient item that pops out"), see also Wykowska and Schubö (2010).
2. Note that although in our experiment the search display was removed and followed by a blank screen before the probe was presented, we use the term SOA to denote the time interval between the onset of the search display and the onset of the probe.
3. It is interesting to note that the effects on P1 were observed a little later in the short SOA condition as compared with the long SOA condition. This might mirror the behavioral results showing longer RTs for the short SOA condition. This might simply indicate that the short SOA condition was slightly more difficult for the probe discrimination task as the temporal distance between search display offset and probe onset was indeed very short (30 msec) and as such might have produced some perceptual interference. However, as the error rates were still very low in this condition (never above 8%), the short SOA was still long enough to produce good performance allowing for meaningful analyses.
4. Interestingly, Luck et al. (1993) found that the P1 was not enhanced for the targets but rather suppressed for the irrelevant singletons as compared with a baseline condition. As such, the authors argue that P1 reflects sensory gain control by suppression of distracting signals. In the case of the present study (and in line with Wykowska & Schubö, 2010), the probe-locked P1 showed enhanced positivity for the targets as compared with a baseline condition ("Off" position). The amplitude of the P1 for probes at the position of the irrelevant singleton did not differ from baseline. Therefore, the effect indicated rather an enhancement of neural activity for probes at the attended location and not suppression of activity at irrelevant singleton positions. The difference might stem from the procedural dissimilarities between the

present experiment and the series of experiments conducted by Luck et al. In the present experiment, the probes were task relevant and the probes were presented after display offset. In the experiments of Luck et al., probes were not relevant to the task and they appeared while the search display was still present. Such a design might have resulted in a stronger suppression effect for the neural activity at the irrelevant position as compared with the present study where enhancement of activity at the target position might have proved more beneficial.

5.   Note that the present argumentation is based on assuming that the N2pc is a marker of the allocation of spatial attention. This assumption is grounded in the literature: Various researchers have interpreted observed N2pc effect as indicating the allocation of spatial attention to one of the visual hemifields (Woodman & Luck, 2003; Eimer, 1996; Luck & Hillyard, 1994). Also the opposite has been suggested; that is, that no N2pc should be observed in cases where spatial attention is not deployed to one of the visual hemifields. For example, no N2pc has been observed in tasks that did not require focusing of attention (e.g., the single-item condition or the "global" condition in Luck & Hillyard, 1994; texture segmentation tasks that involve a more global processing mode rather than local focus of attention in, e.g., Schubö, Schubö, Schröger, & Meinecke, 2004; or for N2pc locked to cues that do not share predefined target characteristics, Eimer & Kiss, 2008; Lien et al., 2008). Therefore, the present dissociation between the observed target-related N2pc and its absence for irrelevant singleton trials speaks in favor of the claim that the irrelevant singleton has not captured spatial attention.

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