

FEATURE ARTICLE

Top-Down Dimensional Weight Set Determines the Capture of Visual Attention: Evidence from the PCN Component

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Visual search for feature singletons is slowed when a task-irrelevant, but more salient distracter singleton is concurrently presented. While there is a consensus that this distracter interference effect can be influenced by internal system settings, it remains controversial at what stage of processing this influence starts to affect visual coding. Advocates of the “stimulus-driven” view maintain that the initial sweep of visual processing is entirely driven by physical stimulus attributes and that top-down settings can bias visual processing only after selection of the most salient item. By contrast, opponents argue that top-down expectancies can alter the initial selection priority, so that focal attention is “not automatically” shifted to the location exhibiting the highest feature contrast. To precisely trace the allocation of focal attention, we analyzed the Posterior-Contralateral-Negativity (PCN) in a task in which the likelihood (expectancy) with which a distracter occurred was systematically varied. Our results show that both high (vs. low) distracter expectancy and experiencing a distracter on the previous trial speed up the timing of the target-elicited PCN. Importantly, there was no distracter-elicited PCN, indicating that participants did not shift attention to the distracter before selecting the target. This pattern unambiguously demonstrates that preattentive vision is top-down modifiable.

Keywords: attentional capture, electroencephalography, N2pc, saliency, visual Search

Introduction

Everyday, humans and other primates spend a large amount of time searching their environment for critical objects, or “targets,” that are necessary to achieve their current action goals. Which object will be attentionally selected first from the multitude of stimuli present in the visual field is assumed to depend on the dynamic interplay between 2 distinct attentional control mechanisms (e.g., Corbetta and Shulman 2002). Setting oneself to certain types of visual information relevant to one’s current intentions (e.g., the color of one’s own car) mediates “expectancy-driven” or “top-down” controlled selection. By contrast, the automatic attraction of attention by salient objects that “pop out” from their surroundings (e.g., the flashing beacons of a police car) is referred to as “stimulus-driven” or “bottom-up” controlled selection. This functional distinction is widely accepted and forms the basis for recent models of visual search and selective attention (e.g., Müller and Rabbitt 1989; Wolfe 1994, 1998; Itti and Koch 2001; Wolfe and Horowitz 2004; Serences and Yantis 2006), albeit the idea of a 2-component framework of attentional selection dates back

at least a century ago, when William James (1890) suggested “active” and “passive” modes of attention.

The Im-/Penetrability of Preattentive Vision

However, the notion that stimulus-driven control, and thus preattentive visual coding, may be influenced by top-down (expectancy-related) factors has repeatedly been challenged (e.g., Theeuwes 1991, 1992, 2004; Mortier et al. 2005; Hickey et al. 2006; Theeuwes et al. 2006). This scepticism has been derived mainly from findings in the so-called “additional-singleton search task,” originally devised by Theeuwes (1991). Typically in this task, participants look for a singleton target, such as an item defined by a unique shape (amongst homogeneous nontarget items possessing a different shape), and then respond to another attribute of the target, such as the tilt, left versus right, of a small line segment inside the target shape. Crucially, the target may not be the only singleton in the display; rather, there may be an additional “distracter” singleton, such as a uniquely colored item (with all the other items being of homogeneous color), which is completely task-irrelevant. In Theeuwes’ (1991) original study, there were trial blocks in which the target was the only singleton in the display (e.g., a green “diamond” among green circles) and blocks in which a distracter singleton was always present (e.g., a diamond plus a “red” circle amongst green circles). Note that the additional singleton was defined in a visual dimension different to that of the target (color rather than shape), and it was perceptually more salient than the target. Comparing search performance between “no distracter” blocks (i.e., diamond-only displays) and “100% distracter” blocks (red distracter singleton present on all trials), Theeuwes observed a significant reaction time (RT) delay of some 25 ms for the distracter condition. Theeuwes explained this interference effect in terms of the “capture of attention,” in bottom-up controlled counterintentional manner, by the highly salient distracter item. That is, even though the color singleton was completely task-irrelevant, visual attention was first deployed to this high-saliency item, before being reallocated to the response-relevant but less salient target item. This basic additional-singleton interference effect has since been replicated in many studies (e.g., Yantis 1993; Theeuwes 1994; Yantis and Hillstrom 1994; Folk and Remington 1998; Theeuwes and Godijn 2002; Proulx 2010; Sawaki and Luck 2010).

Recently, Theeuwes’ notion of attentional capture has received support from an electroencephalogram (EEG) study by Hickey et al. (2006), which concentrated on the Posterior-Contralateral-Negativity (PCN) (i.e., the N2pc [Traditionally, this component has been referred to as N2-posterior-contralateral

(N2pc); however, given its clear-cut independence in terms of timing and activation of the nonlateralized N2 (Shedden and Nordgaard 2001; see also Töllner, Zehetleitner, Gramann, et al. 2011), we prefer to use the term PCN (instead of N2pc) to avoid misleading associations.) component of the event-related potential (ERP) to track the allocation of attention to lateralized singleton positions. Investigating the same stimulus design as used by Theeuwes (1991) (see above), Hickey et al. found that both target and distracter singletons elicited a PCN component when they were presented concurrently in opposite visual hemifields (see Experiment 2 of Hickey et al. 2006). Crucially, the distracter-elicited PCN was found to occur earlier than the target-elicited PCN, indicative of attention being first captured by the more salient distracter item (prior to being reallocated to the target item). That is, again, observers seemed to be unable to overcome the interference associated with the concurrent presentation of a highly salient distracter object.

However, Theeuwes' (1991, 1992, 2004, 2010) strong stance that preattentive visual coding is top-down impenetrable and that focal attention is always deployed to the visually most salient item (location) in the field, has been challenged by a number of studies that used variants of the additional-singleton paradigm (e.g., Folk et al. 1992; Bacon and Egeth 1994; Folk and Remington 1998; Kumada and Humphreys 2002; Leber and Egeth 2006; Müller et al. 2009). For instance, in the study of Leber and Egeth (2006), 2 groups of observers were trained with displays designed to induce 2 different search strategies, or "search modes," before both groups were tested with the same additional-singleton displays. For the first group, the target was 1 of 3 possible forms (square, triangle, and circle) presented among form-homogeneous nontargets (diamonds); by contrast, for the second group, the target was always a circle and the nontargets were form-heterogeneous (consisting of squares, triangles, and diamonds). After training, both groups were tested under identical search conditions: the target was always a circle among diamonds. Importantly, Leber and Egeth observed interference from additional singletons only in the group trained with homogeneous distractors but not in that trained with heterogeneous distractors, even though observers in the latter group received identical stimulation in the test session. In line with the original proposal of Bacon and Egeth (1994), Leber and Egeth took this finding as conclusive evidence for 2 different search modes induced by the different training regimes: 1) a "singleton search" mode, in which observers look for any singleton in the search array so that attention might be captured automatically by the most salient item in the display (as in Theeuwes' experiments) and 2) a "feature search" mode, in which observers (top-down) set themselves to a specific target feature, thereby abolishing the (automatic) capture effect of even more salient distracter singletons (as in Leber and Egeth's experiments).

This idea of allocating processing resources to specific target attributes to optimize target detection bears a close resemblance to the "dimension-weighting account" proposed by Müller and his colleagues (DWA; e.g., Müller et al. 1995; Found and Müller 1996). On this account, visual selection is based on a saliency-based processing architecture (as in Wolfe's "Guided Search"), however, feature contrast signals computed in separate dimensionally organized processing modules (e.g., color, form, and motion) being attentionally weighted prior to their integration by the attention-guiding saliency map units. Given that the total weight available is limited, weighting of

one feature dimension (e.g., form) would lead to enhanced coding of feature contrast signals and, thus, detection of singleton targets defined in this (weighted) dimension, relative to other, nonweighted, dimension (e.g., color; for further details, see Müller and Krummenacher 2006). Based on this architecture, Müller et al. (2009) theorized that the distracter interference observed by Theeuwes (1991) might, in fact, represent one end of a continuum of top-down attentional control, where even maximum downregulation of the weight assigned to feature contrast signals in the distracter dimension is not sufficient to overcome the attracting force of the (after all: physically more salient) distracter singleton. Toward the other end of the continuum, however, the interfering impact of the distracter may be varying depending on the degree of dimension-based top-down control applied.

That is, in conditions in which a distracter singleton is present on all trials (such as in Theeuwes' 100%-distracter condition), top-down distracter suppression should be maximal and consistent, resulting in relatively small interference effects. On the other hand, top-down suppression would be less strong or less consistently applied the less often the distracter singleton appears, resulting in larger interference effects. To test this prediction, Müller et al. (2009) used the same stimuli as in Theeuwes (1991) but systematically varied the proportion of additional distracters within a given trial block. Specifically, in 2 different experiments, observers started with a pure block of trials in which a distracter singleton was either "always" (100% Distracters) or "never" (0% Distracters) presented. In the subsequent trial block, the proportion of distracter singleton was systematically varied (20%, 50%, or 80%, respectively). The RT data showed that the attentional capture effect (by the distracter singleton) was modulated by both the initial experience with distracters and the incentive to suppress them: distracter interference was reduced with relevant practice (100% distracter presence in the initial training block) and with increased incentive of distracter suppression (i.e., increased frequency of distracters in the test phase). Accordingly, this finding contradicts the strong view that preattentive saliency coding is exclusively driven by the physical stimulus attributes of the scene.

Recently, however, Theeuwes (2010) (see also Theeuwes et al. 2000) suggested a "disengagement" explanation to account for the distracter frequency-dependent modulation of the attentional capture effect demonstrated by Müller and colleagues (Geyer et al. 2008; Müller et al. 2009). Specifically, Theeuwes argued that this RT modulation does not reflect variation of the occurrence of capture events but rather the speed with which attention can be disengaged from the distracter singleton (after it has been captured by this stimulus). That is, during the initial sweep of visual coding, attention is automatically attracted by the most salient item in the field: the distracter, which is not influenced by the frequency with which a distracter is presented. Instead, distracter frequency modulates the time required to redirect focal attention away from the distracter to the target location: disengagement takes longer with lower distracter frequencies.

Rationale of the Present Study

The present EEG study was designed to provide a more detailed picture as to whether irrelevant singletons always capture attention in an automatic stimulus-driven fashion—as assumed

by the stimulus-driven account (Theeuwes 1991, 1992) or alternatively, whether attentional capture by irrelevant singletons can be modified on the basis of top-down dimension-based search strategies—as assumed by the dimension-weighting (e.g., Müller et al. 2009) as well as other accounts (e.g., Bacon and Egeth's 1994, "search mode" account and Folk et al. 1992, "contingent-capture" hypothesis). To exactly trace the time course (and direction) of visuospatial attention shifts as a function of distracter frequency in an additional-singleton search task, we combined RT performance with the PCN component, an established electrophysiological marker for examining (millisecond-by-millisecond) the deployment of focal attention in visual space (Eimer 1996; Woodman and Luck 1999). More precisely, this component is a negative-going deflection most pronounced over lateral parietooccipital electrode sites contralateral to the location of an attended stimulus, with neural generators residing within the human homologues of monkey inferotemporal cortex and area V4 (Hopf et al. 2006). To further isolate the PCN from overlapping nonlateralized ERP components, it is recommended to subtract the waveforms at electrodes PO7/PO8 ipsilateral to the target location from contralateral ERPs according to the following formula: $(PO8[\text{left}] - PO7[\text{left}] + PO7[\text{right}] - PO8[\text{right}])/2$, which results in the so-called PCN difference wave. While there is a general consensus that this component reflects the allocation of focal attention based on perceptual stimulus properties (Luck and Hillyard 1994; Eimer 1996; Luck and Ford 1998; Woodman and Luck 1999), there has been a growing interest in the timing of this component, which can be used as marking the transition from the preattentive sensory coding of the stimulus display to the focal-attentional stage of target selection (e.g., Töllner, Zehetleitner, Krummenacher, et al. 2011). Consistent with this, it has been shown that the timing of visual selection is modulated by, for example, stimulus intensity (Brisson et al. 2007), stimulus saliency (Töllner, Zehetleitner, Gramann, et al. 2011), set size (Wolber and Wascher 2005), or intertrial history (Töllner et al. 2008).

Thus, by analyzing the PCN in combination with RT performance, we are able to decide between the 2 alternative (stimulus-driven vs. dimension-weighting) accounts that provide differential predictions concerning the time demands of visuospatial attention shifts (In the present study, the distracter singleton could occur only at positions contralateral to the target location. Accordingly, due to the way in which the (target) PCN difference wave is extracted from the non-lateralized ERPs [see formula above], the presence of a distracter-induced PCN would be indicated by a positive-going deflection that precedes the negative-going deflection elicited by the target.) as a function of distracter frequency: 1) If the distracter frequency effect described by Müller et al. (2009) originates from the speed with which attention can be disengaged from the distracter location (as suggested by Theeuwes 2010), we should observe first a distracter frequency-independent PCN elicited by the distracter singleton, followed by a target-induced PCN, which is delayed for a lower (relative to a higher) additional-singleton probability. 2) If feedforward visual processing is not completely stimulus-driven and can, instead, be intentionally downregulated (Müller et al. 2009), 2 scenarios are possible depending on how efficient the additional singleton can be suppressed: a) If distracter singleton suppression is relatively inefficient, we should observe a distracter-induced PCN (preceding the target-induced PCN), which is enhanced for a lower (relative to

a higher) additional-singleton probability, indicative of a higher (relative to lower) percentage of trials in which attention was indeed captured and allocated to the distracters location. b) If distracter singleton suppression is relatively efficient, we should observe no distracter-induced PCN at all but rather a target-induced PCN which may be delayed for a lower (relative to a higher) additional-singleton probability. The latter would be indicative of prolonged preattentive processing required to directly select the target, that is, without attention being initially captured by the more salient distracter singleton. According to the DWA, such a pattern would arise if the weight assigned to the distracter dimension (e.g., color) can be downregulated to such a degree that the target, even though less salient than the distracter singleton, wins the preattentive competition for focal selection. Furthermore, this (top-)down modulation of distracter weights, which would be inherently associated with an upregulation of target weights, would be the more efficient the more likely the additional singleton can occur.

A second aim of the present study was to investigate whether, and at what stage of processing, distracter interference (on trial N) is further modulated by the presence (vs. the absence) of a distracter singleton on the previous trial ($N-1$). Such a modulation has recently been reported by Müller and his colleagues (Müller et al. 2009; see also Geyer et al. 2008) who found a large influence of the previous trial when distracters were relatively infrequent (20%): the interference caused by a distracter on trial N was greatly reduced when there was also a distracter on trial $N-1$, compared with when there was no distracter; but this effect decreased with increasing distracter probability (50%, 80%). Müller et al. took this as evidence that, with a low distracter frequency (20%), observers were able to reactively enhance top-down control (on trial N) as an immediate consequence of encountering a distracter and its interfering effect on the previous trial ($N-1$; cf. Botvinick et al. 2001; Kerns et al. 2004). To establish the (preattentive vs. postselective) origin of this distracter frequency-dependent intertrial effect, we additionally examined RT performance in association with the PCN component as a function of "distracter frequency" (25% vs. 50%), "distracter presence on trial N " (present/absent), and "distracter presence on trial $N-1$ " (present/absent). If observers were indeed able to actively enhance (top-down) distracter singleton suppression at the preattentive coding stage after encountering a distracter (under conditions of low distracter probability), one should observe a speedup of target selection—as indicated by the PCN wave—in the subsequent trial episode.

Materials and Methods

Participants

Thirteen observers (4 females) took part in this study. Their ages ranged from 20 to 30 (median 25) years. All had normal or corrected-to-normal vision and reported no history of neurological disorders. Observers gave their written informed consent and were either paid or, alternatively, received course credit for participating.

Stimuli, Task, and Study Design

The visual search array (see Fig. 2) consisted of 38 colored bar stimuli arranged along the circumferences of 3 (concentric) imaginary circles around a white central fixation point. The inner, middle, and outer circles consisted of 8, 12, and 18 items placed at an eccentricity of 4.5°,

8.5°, and 12.5° of visual angle, respectively (see Fig. 2). All bar stimuli were 0.6° wide, 2.7° high, and had a gap (of width 0.216°) either at the top or bottom. All stimuli were presented against a black background. On each trial, the stimulus display contained a target singleton tilted $\pm 15^\circ$ relative to the remaining 37 vertically oriented items. The target singleton and all nontargets (except the additional-singleton distracter if present) were pink (3.2 c/m² CIE [0.28, 0.14]). The position of the target singleton was selected randomly from 1 of the 6 lateral positions of the middle circle. On some trials, an additional distracter singleton (cyan; 78.3 c/m² CIE [0.21, 0.30]) could occur at 1 of the 3 lateral positions of the middle circle contralateral to the target singleton. The likelihood of an additional task-irrelevant distracter singleton occurring was either 25% or 50%, depending on the respective experimental condition. Observers were instructed to maintain central eye fixation throughout the experiment and to give a speeded forced-choice response indicating the gap location (top vs. bottom) of the orientation target, using their left or right thumb to press the left or the right mouse button, respectively. The stimulus-response mapping was counterbalanced across participants.

Observers were seated in a dimly illuminated and sound-attenuated chamber (Industrial Acoustics Company GmbH). The stimuli were presented on a 17" computer screen, placed at a viewing distance of approximately 75 cm. One experimental session consisted of 24 blocks of 84 trials each, resulting in a total of 2016 trials. A trial started with the presentation of a central, white fixation point for 500 ms, followed by the search display for 200 ms. Trials were terminated by the observer's response or after a maximum duration of 1000 ms. During the intertrial interval, a central white fixation point was presented for a variable duration uniformly distributed between 950 and 1050 ms. In case of a response latency longer than 1000 ms or an erroneous response, the word "FEHLER" (German word for "error") was centrally presented for 1000 ms, providing direct error feedback. Half of the observers started with an additional-singleton probability of 25%, whereas the other half started with a 50% probability. After the first experimental half (=12 blocks), the likelihood of additional-singleton occurrence (25% vs. 50%) was reversed. Prior to the start of each experimental half, observers were explicitly informed about the probability of an additional task-irrelevant singleton occurring. Prior to the start of the experiment, one block of practice was performed to ensure a proper stimulus-response mapping. After each block, participants received summary performance statistics (mean error rate and RT).

EEG Recording and Data Analysis

The EEG was recorded continuously from 64 scalp electrodes with a sampling rate of 1000 Hz. Electrodes were mounted on an elastic cap (Easy Cap, FMS), with positions corresponding to the 10–10 System (American Electroencephalographic Society 1994). Horizontal and vertical electrooculogram was monitored by means of electrodes placed at the outer canthi of the eyes and, respectively, the superior and inferior orbits. Electrophysiological signals were amplified using a 0.1 to 250-Hz band-pass filter using BrainAmp amplifiers (BrainProducts, Munich) and filtered offline with a 1 to 40-Hz band-pass (Butterworth zero phase, 24 dB/Oct). All electrodes were referenced to Cz during data acquisition and rereferenced off-line to linked mastoids. Impedances were kept below 5 k Ω . Prior to epoching the EEGs, an independent component analysis (ICA), as implemented in the Brain Vision Analyzer software (BrainProducts, Munich), was run to identify and exclude components that represent blinks and/or horizontal eye movements. The continuous EEG was then epoched from 200 ms prior up to 500 ms after search display onset, using the 200 ms prestimulus interval for baseline correction. Only trials with correct responses and without artifacts—defined as any signal exceeding ± 60 μ V, bursts of electromyographic activity (permitted maximal voltage steps per sampling point of 50 μ V), and activity lower than 0.5 μ V within intervals of 500 ms (indicating dead channels)—were selected on an individual-channel basis, prior to averaging. The (target-related) PCN component was measured at lateral parietooccipital positions PO7/PO8, subtracting ERPs ipsilateral to the side of the target singleton from contralateral ERPs. Note that, due to the way by which the (target) PCN difference wave is extracted from the nonlateralized ERPs (see formula above), the presence of

a distracter-induced PCN would be indicated by a positive-going deflection that precedes the negative-going deflection elicited by the target item. Accordingly, in order to test the existence of an initial attention shift to the distracter location in the present experiment, we defined distracter-induced PCN latencies individually as the maximum positive deflection in the 150 to 300-ms time window poststimulus, whereas target-induced PCN latencies were determined as the maximum negative deflection in the 150 to 350-ms time window following stimulus onset. Both distracter and target PCN amplitudes were calculated averaging 5 sample points before and after the maximum deflections. PCN onset latencies were determined using the Ulrich and Miller's (2001) jackknife-based scoring method, which defines the onset as the point in time at which the amplitudes reaches a specific criterion relative to the prestimulus baseline. As suggested by Ulrich and Miller (2001), we used 50% maximum amplitude as an optimal criterion for determining the onset of stimulus-locked ERP potentials.

Results

Behavioral Data

RTs and error rates were examined in separate analyses of variance (ANOVAs) with the factors Distracter Presence (present, absent), Distracter Frequency (25%, 50%), and *N-1* Distracter Presence (present, absent). For RTs, the main effect of Distracter Presence, $F_{1,11} = 66.11$, $P < 0.001$ and the interaction between Distracter Presence and Distracter Frequency, $F_{1,11} = 7.30$, $P < 0.020$, were statistically significant. As illustrated in Figure 1 (lines), participants were overall slower to respond when a distracter singleton was presented simultaneously with the target singleton compared with when the target was the only singleton (499 vs. 491 ms). Importantly, however, this distracter interference effect was modulated by the probability of a distracter singleton occurring. As confirmed by post hoc contrasts (Tukey HsD), the interference effect was increased from 5 ms in the high-frequency condition (492 vs. 497 ms, $P < 0.02$) to 12 ms in the low-frequency condition (491 vs. 503 ms, $P < 0.001$). For error rates, only the main effect of Distracter Presence was significant, $F_{1,11} = 8.96$, $P < 0.001$: error rates were increased when a distracter was present rather than absent (7.4% vs. 5.8%).

Electroencephalographic Data

Figure 2 shows grand average ERP waveforms elicited by target displays that either did or did not contain an additional (more

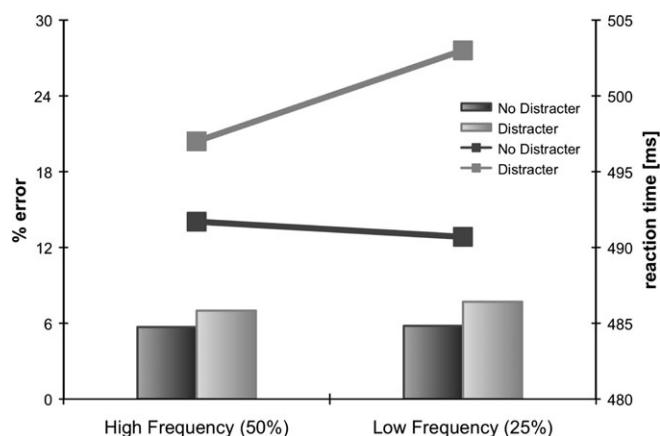


Figure 1. Reaction times (lines) and error rates (bars) as a function of Distracter Presence and Distracter Frequency.

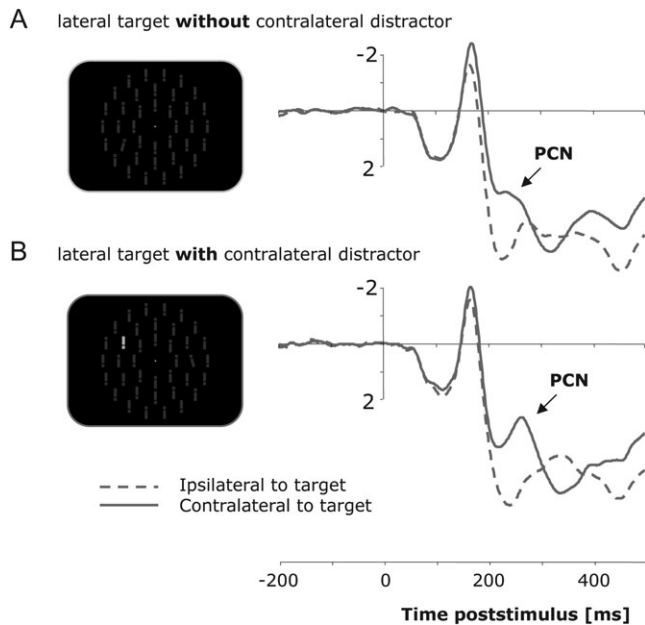


Figure 2. Grand-averaged event-related brain potentials elicited contra- and ipsilateral to the target location at electrodes P07/P08 in the 500-ms interval following stimulus onset, relative to a 200-ms prestimulus baseline. (A) Grand-averaged ERPs elicited by search arrays that contained a lateral target and no distracter singleton. (B) Grand-averaged ERPs elicited by search arrays that contained a lateral target and a contralateral distracter singleton.

salient) distracter singleton (bottom and top panels, respectively). Separate waveforms for contra- and ipsilateral targets relative to the hemisphere of the recording electrode are shown from lateral parietooccipital scalp sites (P07/P08). For both conditions, a (target-related) PCN component can be seen as a more negative (i.e., less positive) voltage starting at approximately 150 ms poststimulus for “no distracter trials” and at approximately 200 ms poststimulus for “distracter trials.”

To segregate the (target-induced) PCN component from the overlapping nonlateralized ERP components, Figure 3A shows the corresponding contralateral-minus-ipsilateral difference waveforms as a function of “Distracter Presence” and “Distracter Frequency.” As can be seen from this figure, the rise of the PCN was markedly delayed and more pronounced for trials on which a distracter singleton was present (rather than absent). In addition, for distracter trials, the PCN was more delayed the lower (relative to higher) the likelihood that an additional distracter could occur, and when there was no distracter presented on the preceding trial (see Fig. 4A). This pattern of a delayed as well as more enhanced rise of the target-related PCN is further demonstrated by the PCN scalp distributions (see Figs 3C and 4C), which—in line with previous studies (e.g., Hopf et al. 2002; Töllner et al. 2011)—revealed this difference wave to be strongest over extrastriate visual areas. Critically, however, the data revealed no indication of distracter-induced positive-going deflection preceding the target-induced negative-going deflection (PCN). The absence of a positive-going deflection contradicts the notion that focal attention is always initially shifted to the most salient (i.e., in the present study, the distracter singleton) item in the field and must be then disengaged from that (distracter) location in order to select less salient items (i.e., the target singleton).

These observations are statistically substantiated by repeated-measure ANOVAs with the factors Distracter Presence (present,

absent), Distracter Frequency (25%, 50%), and *N-1* Distracter Presence (present, absent). For target-related PCN latencies, this ANOVA revealed a significant main effect of Distracter Presence, $F_{1,11} = 63.59$, $P < 0.001$ (230 vs. 260 ms), which interacted with both Distracter Frequency, $F_{1,11} = 6.161$, $P < 0.030$, and *N-1* Distracter Presence, $F_{1,11} = 13.06$, $P < 0.004$. Subsequent post hoc contrasts confirmed that the distracter interference effect was scaled down in the high- (21 ms, $P < 0.001$) relative to the low-frequency condition (38 ms, $P < 0.001$) as well as when the previous trial also contained a distracter singleton compared with when it did not (25 ms, $P < 0.001$ vs. 34 ms, $P < 0.001$). For target-related PCN amplitudes, only the main effect of Distracter Presence reached significance, $F_{1,11} = 31.69$, $P < 0.001$, reflecting enhanced (target-induced) PCN activations (-3.72 vs. -2.87 μV) for trials on which an additional distracter singleton was presented simultaneously in the hemifield contralateral to the target singleton.

To statistically examine the numerical absence of a distracter-induced PCN as suggested by Figures 3A and 4A, we further compared “fast” and “slow” distracter trials (as defined by an RT median split, on an individual subject level), thereby testing the possibility that participants might have been more distracted—owing to possibly more frequent initial attention shifts to the distracter location and, associated with this, a more pronounced positive distracter-induced PCN—in “slow” than in “fast” distracter-present trials (see Fig. 5). However, for both RT groups, this analysis revealed the mean amplitudes (as defined as the average of 5 sample points before and after the maximum positive deflection in the 150 to 300-ms time window poststimulus) to be negative: -0.33 μV [95% confidence interval: -0.77 to 0.11 μV] for the fast and -0.24 μV [95% confidence interval: -0.63 to 0.15 μV] for the slow RT group, respectively. Statistically, the confidence intervals reject the hypotheses that a (theoretical) distracter-induced PCN (indicative of an initial attention shift to the distracter location) would have been greater than 0.15 μV , which corresponds to 4% of the negative target-induced PCN activations. Consequently, if there were any attention shifts to the distracter, the activation strength of those shifts would have been less than 4% of the activation strength of a shift to the target.

Discussion

By examining electrocortical brain responses, the present study was designed to yield novel insights into the currently controversial issue of whether preattentive vision is purely bottom-up driven by physical stimulus attributes (e.g., Hickey et al. 2006; Theeuwes 2010) or, alternatively, whether it can be—at least to some degree—top-down modulated by internal system settings (e.g., Folk et al. 1992; Müller et al. 1995). To study this question, we used an additional-singleton paradigm adopted from Müller et al. (2009), in which the probability of the task-irrelevant additional singleton was systematically varied. The behavioral data were as expected from previous studies (e.g., Geyer et al. 2008; Müller et al. 2009): speeded RTs (Note that, due to “temporal smearing,” ERP latency differences cannot be simply equated with RT differences.) were found for conditions with a higher (as compared with a lower) additional-singleton probability, indicating that distracter singleton suppression was the more efficient the more likely a distracter singleton could appear.

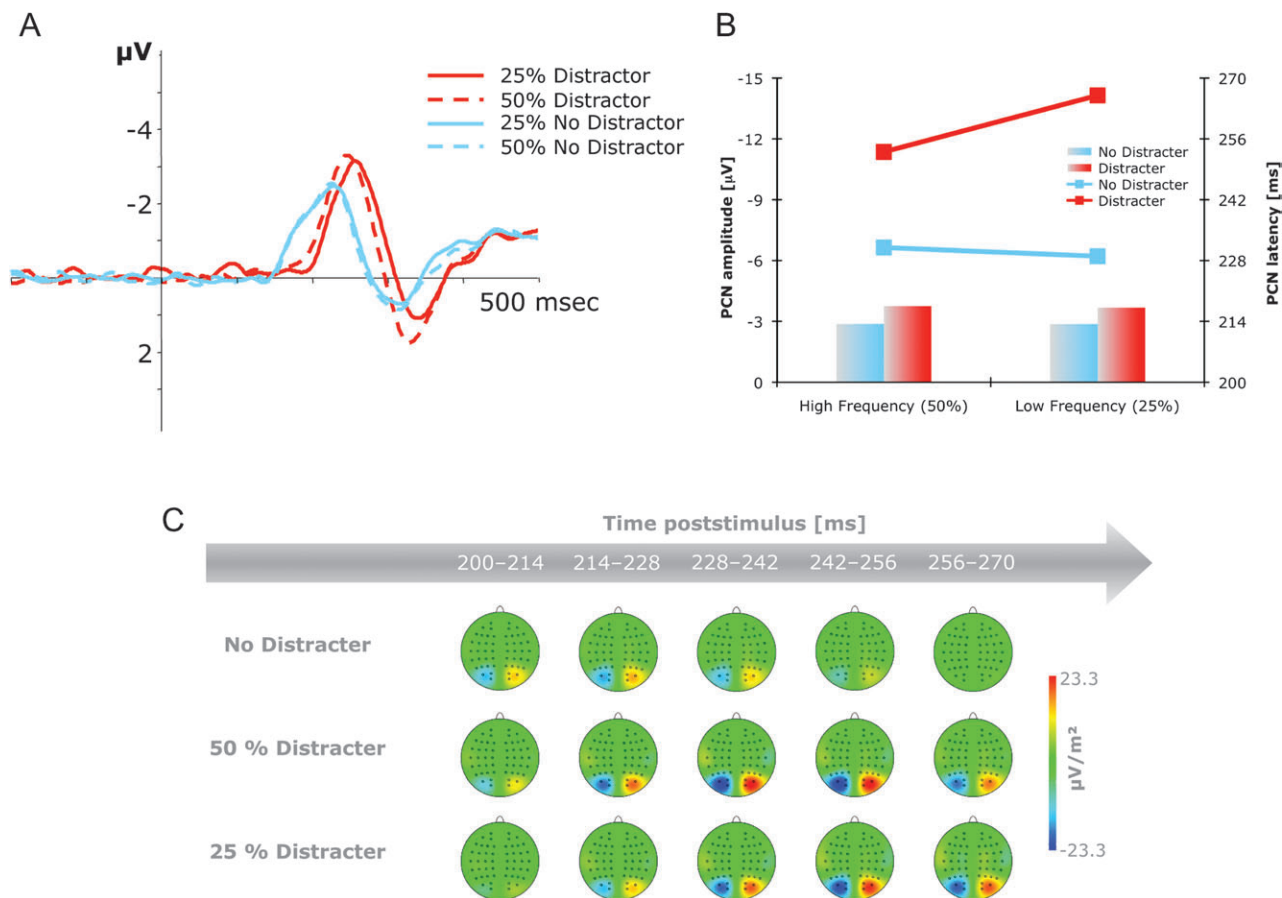


Figure 3. Grand-averaged PCN difference waveforms as a function of Distractor Presence and Distractor Frequency. (A) PCN difference waves obtained by subtracting ipsilateral from contralateral activity at electrodes PO7/PO8 in the 500-m interval following stimulus onset, relative to a 200-ms prestimulus baseline. (B) PCN latencies (lines) and PCN amplitudes (bars). (C) Topographical maps of PCN scalp distributions in the 200 to 270-ms interval following stimulus onset. These maps were computed by mirroring the contra-ipsilateral difference waves to obtain symmetrical voltage values for both hemispheres (using spherical spline interpolation).

Probability Effects on Distracter Singleton Suppression

Our electrophysiological data demonstrate that this effect of distracter probability originates from processing stages located prior to focal-attentional target selection. This is indicated by the timing of the PCN—a component that is conventionally used to trace shifts of focal attention in visual space (e.g., Eimer 1996; Woodman and Luck 1999). The target-induced PCN was elicited earlier when the likelihood of an additional singleton was higher (relative to lower). Of theoretical importance, there was no indication of a distracter-elicited PCN preceding the target-elicited PCN. Recall that such a pattern should have been observed if focal attention were indeed captured initially by the distracter singleton (the item or location with the highest feature contrast), before being disengaged and redirected to the target item—a key assumption of Theeuwes' (2010) *stimulus-driven* account. The failure to observe a proper distracter-related PCN in the present study provides strong evidence that the differential RT costs associated with rare versus frequent task-irrelevant distracter singletons cannot be attributed to an initial automatic attention shift to the more salient distracter location (with both rare and frequent distracters) and, following this, prolonged times required to disengage attention from this location and reallocate it to the target location with rare (as compared with frequent) distracters. Instead, our findings indicate that the simultaneous presentation of a distracter, especially a rare distracter,

prolongs the preattentive times required to directly select the target item, consistent with a modulation of an attentional “filtering cost” (cf. Kahneman et al. 1983; Folk and Remington 1998; Becker 2007; Wykowska and Schubö 2011).

Besides these PCN timing effects, the presence (but not likelihood) of the distracter singleton was found to further determine the activation strength of the PCN. That is, a stronger PCN was elicited on trials on which a distracter did (vs. did not) occur concurrently in the hemifield contralateral to the target. This activation pattern is in close correspondence with Hopf et al. (2002), who suggested that the processes underlying the PCN primarily reflect the suppression of distracter interference. Accordingly, in the present study, enhanced PCN amplitudes for distracter-present trials may reflect the strengthened operation of suppressive processes so as to effectively shield target selection against interference generated by the distracter singletons (It should be noted that Hickey et al. (2006) [Experiment 1] found target-related PCN amplitudes to be enhanced for distracter-absent [relative to present] trials. Crucially, however, by extracting amplitude values [from contra- and ipsilateral waveforms] over identical fixed time windows, they did not acknowledge that the timing actually differed between these conditions. Thus, it might well be that the time window analyzed for distracter trials in the study of Hickey et al. covered only half of the actual difference.).

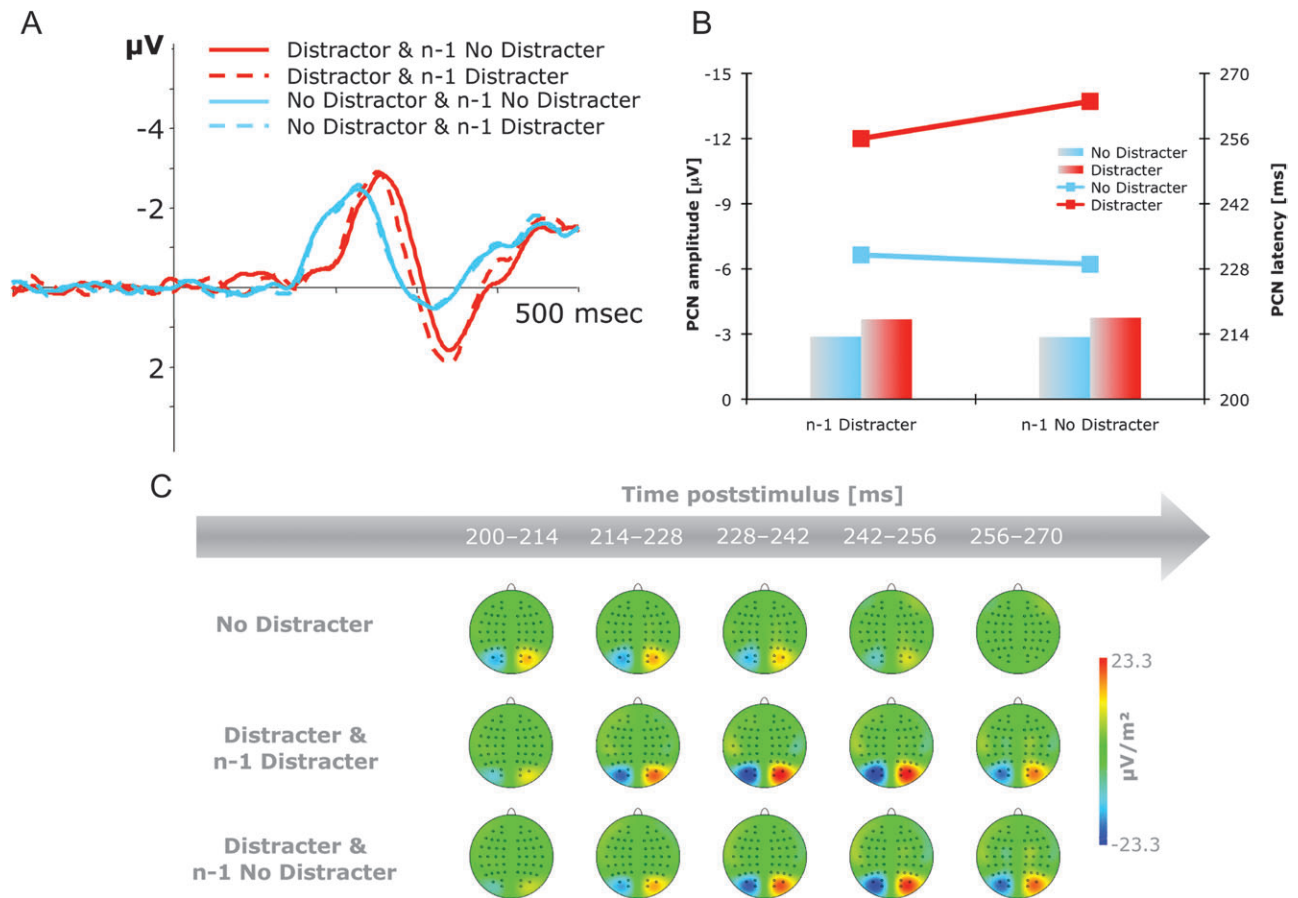


Figure 4. Grand-averaged PCN difference waveforms as a function of Distracter Presence and *n-1* Distracter Presence. (A) PCN difference waves obtained by subtracting ipsilateral from contralateral activity at electrodes P07/P08 in the 500-ms interval following stimulus onset, relative to a 200-ms prestimulus baseline. (B) PCN latencies (lines) and PCN amplitudes (bars). (C) Topographical maps of PCN scalp distributions in the 200 to 270-ms interval following stimulus onset. These maps were computed by mirroring the contra-ipsilateral difference waves to obtain symmetrical voltage values for both hemispheres (using spherical spline interpolation).

Following the DWA (e.g., Müller et al. 1995, 2009, 2010), the more (relative to less) frequent presentation of distracter singletons (defined in a dimension other than the target) would help participants to more efficiently shield against their interference. This shielding is accomplished at preselective processing stages through a downregulation of the weights assigned to feature contrast signals in the distracter dimension. Given that the total amount of attentional weight is limited (a key assumption of the DWA; for a modality-weighting account, see also Töllner et al. 2009), down modulation of the weight for the distracter dimension (e.g., color) would automatically translate into an increase of the weight for the target dimension (e.g., orientation). This, in turn, would help the target to win the preattentive competition for selection at the level of the attention-guiding supradimensional saliency map, even though it is physically less salient than the distracter item. This is not to say that the human visual system can down-regulate any task-irrelevant visual signal, independently of its absolute physical salience, to such an extent that the signal would no longer cause interference. Rather, with task-irrelevant stimuli of very high feature contrast, our top-down control mechanism may no longer be able to prevent them from capturing attention. Arguably, this limited ability to prevent interference from stimuli salient in a nonweighted dimension would be evolutionarily adaptive, permitting such

signals to alert us to objects of potential danger in our environment (e.g., predators, etc.). However, as we have demonstrated, simply the physical saliency difference between the 2, target and distracter, singletons does not necessarily determine which 1 of the 2 will be selected first (for a discussion of the comparative evidence for the various alternative accounts, see also Müller et al. 2009).

Our results are in close resemblance with a number of recent EEG studies which likewise found perceptual/attentional ERP components, and thus feedforward visual processing, to be modulated by top-down factors such as “feature set” (Zhang and Luck 2009), “dimensional set” (Töllner et al. 2010), or “task set” (Eimer and Kiss 2008). For instance, Töllner et al. (2010) investigated whether participants would be able to intentionally set themselves to a specific visual dimension in order to improve their search performance for pop-out signals defined in this dimension. To realize this, participants were provided with preknowledge (i.e., semantic word cues) as to the dimension likely to define the upcoming singleton target, on a trial-by-trial basis. In addition, a compound-search task was employed, in which the feature dimension (color or shape) that singles out the target from its surround is dissociated from the feature (vertical or horizontal) that determines the motor response. The results showed that, even though the semantic precue contained no information whatsoever regarding the response-defining

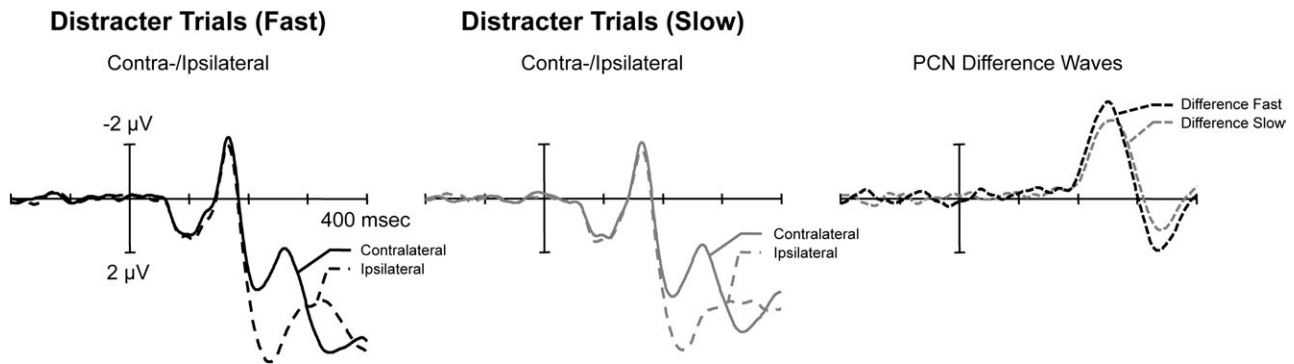


Figure 5. Grand-averaged event-related brain potentials elicited at electrodes PO7/PO8 in the 400-ms interval following stimulus onset, relative to a 200-ms prestimulus baseline, for fast (black lines) and slow (gray lines) distracter-present trials, respectively. Left panel: Contra- and ipsilateral waveforms elicited by the fast RT group. Central panel: Contra- and ipsilateral waveforms elicited by the slow RT group. Right panel: PCN difference waveforms obtained by subtracting ipsilateral from contralateral activity for both fast and slow distracter trials.

feature, participants reacted faster, associated with both shorter latencies and enhanced amplitudes of the PCN, when the target was validly (relative to invalidly) precued. This unequivocally demonstrates that dimensional expectancies modulate the time demands of visual (pop-out) target selection.

This is consistent with Zhang and Luck (2009) who found that (top-down) feature-based attention can modulate feedforward sensory activity, as reflected by the P1 wave (for dimension-based P1 cueing effects, see also Gramann et al. 2010). They presented a continuous stream of intermixed red and green dots in one visual hemifield (e.g., on the left), with participants instructed to attend to either the red or the green dots in this hemifield in order to detect occasional luminance decrements in the respective target color. Additionally, probe arrays consisting of only red or only green dots were flashed in the opposite (in the example, the right) hemifield. Analyzing the brain activity elicited by the task-irrelevant probe arrays presented intermittently in the nonattended hemifield, Zhang and Luck observed P1 amplitudes over the cortex contralateral to be significantly enhanced when the probe arrays were flashed in the attended (as compared with the unattended) color. This, again, provides strong evidence for an (space-independent) attentional influence on feedforward sensory processing and appears inconsistent with the view (advocated by Hickey et al. 2006; Theeuwes 2010) that top-down set can bias visual selection only after 150 ms poststimulus.

Previous Trial History Effects of Distracter Singleton Suppression

A second aim of the present study was to obtain further insight into whether, and to what degree, experiencing a distracter on the previous trial would influence distracter interference on the current trial. Behaviorally, such a pattern has recently been described by Müller et al. (2009) (see also Geyer et al. 2008) who found the interference effect caused by a distracter on the current trial N to be substantially increased when there was no distracter (relative to when there was one) on the previous trial $N-1$; crucially, however, this effect was evident only with infrequent distracters (probability of 20%) but absent with relatively frequent distracters (i.e., probabilities of 50% and 80%). To explain this pattern, Müller and colleagues proposed (following Botvinick et al. 2001) that, with low distracter frequency, encountering a distracter on the preceding trial helps the observer to reactively enhance online

(top-down) control, so as to effectively shield target selection from the potential interference of competitive signals defined in the distracter dimension (with high distracter frequency, by contrast, this shielding is applied rather consistently, whether or not a distracter is encountered on the preceding trial). From the perspective of the DWA, enhanced top-down control of selection processes should again modulate preattentive selection times, involving a reactive shift of dimensional weight (away from the distracter) toward the target-defining dimension.

Our electrophysiological data exactly support this view: for conditions of simultaneous distracter singleton presentation, visual (target) selection times, as indicated by the target-induced PCN latencies, were significantly faster when the display on the previous trial did (vs. did not) contain a distracter singleton. However, in contrast to Müller et al. (2009), this intertrial effect of distracter singleton suppression was not further modulated by distracter probability. One possible reason for the absence of such an interaction might lie in the particular distracter frequencies used in the present study, namely, 25% and 50%, whereas Müller et al. had also used one condition with a much higher frequency, 80% (and greater differences between the frequencies introduced). In the present study, the difference between the 2, relatively low, distracter frequencies (25% and 50%) may have been too small for the interaction effect to approach statistical significance.

Conclusion

To conclude, the findings of the present EEG study add to the mounting evidence (e.g., Zhang and Luck 2009; Töllner et al. 2010) that the initial feedforward sweep of visual information through the brain is not exclusively driven by physical stimulus attributes. This is attested by the present observations that 1) attention was not automatically captured by the location exhibiting the highest feature contrast (i.e., distracters failed to elicit a PCN) and 2) the interference associated with the occurrence of a distracter singleton (i.e., the distracter's effect on the timing of the target-elicited PCN) interacted with both distracter expectancy and intertrial history. These results provide, to our knowledge, the first unambiguous demonstration that both high (relative to low) distracter expectancy and experiencing a distracter on the previous trial can influence

the preattentive time demands for directly selecting a less salient target item. Both observations refute the strong stimulus-driven view advocated by Theeuwes (2010) and provide support for models (such as the DWA) that envisage preattentive visual coding processes to be modifiable—at least to some degree—by internal system settings that are under top-down control.

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Notes

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