The P4pc: An Electrophysiological Marker of Attentional Disengagement?

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Abstract

The processing of successive targets requires that attention be engaged and disengaged. Whereas attentional engagement can be studied by means of the N2pc component of the event-related potential (ERP), no ERP component has been linked to attentional disengagement. Here, we report the finding of such a component using an RSVP paradigm with multiple, successive targets and with a spatial-cuing paradigm. In both experiments, swift disengagement of attention was necessary to attend to subsequent targets. A distinct waveform following the N2pc, which we call the P4pc (Positivity 400 ms post-target posterior contralateral), was found. The P4pc was found when a lateralized cue indicated that attention would be needed for the processing of a target at either the same or a different location as the cue, but not when only the cue was to be responded to, indicating that the need to disengage attention is a prerequisite for the P4pc to occur. We expect the P4pc to provide a valuable addition to the set of electrophysiological measures used to study the dynamics and mechanisms of visual attention and visual search.

Keywords: Event-related potentials (ERP), N2pc, P4pc, attention engagement, attention disengagement.
Abbreviations: P4pc: Positivity 400 ms post-target Posterior Contralateral

1. Introduction

In many search tasks, the processing goal has been achieved if the target is found and relevant target information extracted. However, when multiple targets are present, either simultaneously or in close temporal proximity, an additional act of attentional control is required: As soon as a target has been selected and relevant information extracted, attention must be disengaged from that target to allow selection of potential other targets. An important question is whether disengagement is an active process whereby a previous engagement of attention to a location or object is undone (e.g., Posner et al., 1984) or simply a consequence of re-engagement elsewhere (e.g., Cohen et al., 1994).

According to Posner et al. (1984), attentional disengagement occurs in reaction to the onset of a new target, and must precede the moving of attention to and subsequent engagement at that target. From this perspective, disengagement and engagement of attention are seen as distinct processes characterized by different neural mechanisms located in different areas of the brain (Posner & Petersen, 1990): The parietal lobe is responsible for disengagement of attention and the pulvinar for attention engagement. Cohen et al. (1994) have challenged the claim that disengagement and engagement of attention are mediated by separate mechanisms. They base their claim on simulations with a model of selective attention in which selection is based on competitive interactions between attention to different regions of space. Using simulations of "lesions" to the model they showed that the deficits in disengagement on which Posner et al.'s hypothesis of a separate disengagement mechanism is based can be accounted for solely in terms of "competition between sources of top-down support for perception" (p. 385).

The spatially cued simple reaction time task used by both Posner et al. (1984) and Cohen et al. (1994) to reach conclusions about disengagement is bottom-up in nature. Two spatial locations are indicated, one in the right and one in the left visual field, and a cue at one location is followed by a target at either the same (validly cued) or opposite (invalidly cued) location. Thus, capture of attention by the cue and by the target drives performance. We hypothesize that disengagement of attention may also occur in a proactive, endogenous manner in anticipation of possible simultaneously or subsequently presented targets. In this sense disengagement would reflect the strategic release of attention from the currently attended object in order to allow reorienting of attention towards the next object or its actual or expected location. Such proactive attentional disengagement can be seen as an act of cognitive control, resembling preparatory control in task-switching and overlapping-task performance (De Jong, 1995; Luria & Meiran, 2005; Schneider & Logan, 2007; Schubert, 2008). Endogenous disengagement is arguably a critical component of attentional processing in many tasks, such as search in complex environments, yet it has received little study (Wolfe & Horowitz, 2008).

Attentional processes have been functionally linked to event-related brain potential (ERP) measures (e.g., Kiss et al., 2008b; Luck, 2005). The N2pc (Negativity 200 ms post-target posterior contralateral) component, in particular, has become an increasingly popular tool in the investigation of attentional processing (e.g., Kiss et al., 2008b; Woodman & Luck, 1999, 2003). The N2pc is typically observed in the N2 latency range

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(200-300 ms poststimulus) at posterior electrodes contralateral to the side of a laterally presented visual target. Source analyses based on MEG recordings have localized its primary neural generators in ventral occipitotemporal cortex (Hopf et al., 2000). The N2pc appears to reflect the attentional selection of target stimuli or target enhancement (attentional engagement, Eimer, 1996; Mazza et al., 2009b,a) or the attentional suppression of nontargets (Luck & Hillyard, 1994).

Whereas the relationship between attentional selection or engagement and the N2pc is well established (Kiss et al., 2008b), no specific ERP component has been linked to disengagement of visuospatial attention. If attentional engagement and disengagement are closely related but functionally opposite processes (Cohen et al., 1994), one might expect disengagement to be reflected by an ERP component with a similar scalp distribution but opposite polarity to the N2pc. Suggestive evidence for such a disengagement-related component was reported in a recent study of Lien et al. (2008, see also Eimer & Kiss, 2008). Lien et al. presented a lateralized non-informative cue 150 ms before the onset of a target display consisting of four letters. When the cue shared a target-defining color, it elicited an N2pc, indicating contingent attentional capture. Interestingly, in two experiments this cue-related N2pc was followed within 100 ms by an even stronger component of opposite polarity which the authors referred to as a "reversed N2pc". However, rather than linking this second component to active disengagement from the cue, the authors suggested, in line with Woodman & Luck (1999, 2003), that it might represent a regular N2pc reflecting the reorienting of attention back to the central fixation cross to correct for the erroneous capture of attention by the cue (see Seiss et al., 2009, for a similar interpretation of the finding that target-related ERPs were followed by a reversed N2pc when targets appeared at an invalidly cued location, but not at a validly cued one).

Other studies showing the reversed N2pc include Akyrek et al. (2010a); Brisson & Jolicoeur (2007a); Eimer et al. (2009); Girelli & Luck (1997); Leblanc et al. (2008). In many cases the presence of the component was neither noted nor statistically evaluated. Moreover, whereas the finding of an initial N2pc followed by a reversed N2pc is consistent with the idea that the latter component reflects attentional disengagement prior to subsequent reorienting in these studies, the paradigms used in these studies do not preclude an account in terms of initial attentional engagement by a lateralized target followed by reorienting of attention back to fixation or to the opposite hemifield. The latter account is parsimonious and has the attraction of being based on the well established link between the N2pc and attentional engagement. However, because the hypothesis that the reversed N2pc might reflect attentional disengagement of lateralized targets was not tested, it is premature to accept the reorienting account.

The two experiments reported here were designed to compare the disengagement and reorienting hypotheses. In both experiments two or more lateralized targets were presented in close succession. In the critical conditions, subsequent targets were presented at the same lateral location or in the same hemifield. Participants were informed about the target locations and task requirements compelled them to make use of this information. That is, these conditions were designed to require disengagement from one target and reorienting of attention to the upcoming target without returning attention to fixation or shifting to the opposite hemifield. If the reversed N2pc reflects disengagement, it should be present even in these conditions in which a lateralized shift of attention was not required. On the other hand, a reorienting account of the component would predict either no additional N2pc or an N2pc of the same polarity as that to the first target as any reorienting should not involve a shift of attention in the opposite horizontal direction (e.g., Woodman & Luck, 2003).

In Experiment 1 we used a rapid serial visual presentation (RSVP) paradigm with two simultaneous streams presented in the left and right visual fields, with each stream containing multiple potential targets. Participants were instructed to attend to one (focused-attention condition) or both (divided-attention condition) streams and to respond whenever they saw a target. The results showed an N2pc for targets that was followed at approximately 400 ms post-target onset by a second component of opposite polarity but similar scalp distribution. Because we believe that the functional meaning of this second component is different from the one of the N2pc, we refer to it as P4pc (positivity 400 ms post-target posterior contralateral), and argue that the results are consistent with the notion that it represents a psychophysiological marker of attentional disengagement. In Experiment 2 we tested the generality of the findings of Experiment 1 by using a more temporally discrete (cue + target) design that allowed for a more rigorous test of the reorienting and disengagement hypotheses.

2. Experiment 1

In this experiment we pitted the disengagement and reorientation hypotheses against each other by presenting two simultaneous 6-Hz RSVP streams containing multiple targets (the digit "5") to the left and right visual fields. The participant's task was to detect the targets in either one or both streams. The relative timing of targets needed to allow a reversed N2pc to be isolated in the ERP was determined in a series of pilot experiments. In fact, on one hand, the interval separating targets should be short to compel swift disengagement from the previous target and to tightly time-lock the reversed N2pc to the presentation of the first target. On the other hand, temporal overlap between disengagement from the first target and orienting to the second target, with the latter presumably associated with a regular N2pc, could mask the presence of a disengagement-related reversed N2pc in the ERP. Based on the results of the pilot studies, we set the average inter-target interval at a value that represented a suitable compromise between these opposing constraints.

At the beginning of each trial, a cue instructed participants to direct their attention to the left or the right stream (focused-attention condition) or to divide attention equally across the streams (divided-attention condition). In the divided-attention condition, reorientation would presumably involve redirecting attention to fixation or returning it to a divided state (e.g., Lien et al., 2008; Seiss et al., 2009). Thus, the finding of a reversed

N2pc in the divided-attention condition would be consistent with either disengagement or reorientation. In the focused-attention condition, however, the finding of a reversed N2pc would provide strong support for the disengagement hypothesis because reorienting or re-engagement in this condition should not involve a horizontal shift of visuospatial attention.

In line with the results of Kiss et al. (2008b), we expected to find the N2pc for relevant targets in both the focused and divided attention conditions. No predictions regarding N2pc amplitude differences between attention conditions were made, as previous studies have produced somewhat conflicting effects of advance spatial information on N2pc amplitude (e.g., see Kiss et al., 2008b for evidence that N2pc amplitude is not affected by preparatory information and Praamstra, 2006, for evidence that N2pc amplitude is affected by preparatory information).

2.1. Material and Methods

2.1.1. Participants

Fourteen healthy individuals (7 males) between the ages of 20 and 30 (mean = 24.3 years, s.d. = 4.9) participated in the experiment. The study adhered to the Declaration of Helsinki and was approved by the local ethics committee. Informed consent was obtained from all participants.

2.1.2. Stimuli and apparatus

Stimuli were presented on a 17” CRT monitor (800 x 600 pixels at 144-Hz). Stimuli were the distractor letters “A” through “K” and “P” and the target number “5”. Two sequences of 60 distractors and targets were displayed on each trial, one in the left and one in the right visual field, 5.7° lateral to a central fixation point against a flickering background. The flickering background was included to test a secondary hypothesis not central to the thesis of the present work (Toffanin et al., 2009, see). The stimulus sequences were randomized, with the constraint that repetitions and simultaneous presentation of a given character in the left and right display were not allowed. Characters were displayed in a blue (RGB: 0, 0, 255) Tahoma 48-point font (corresponding to a width of 1.4° and a height of 1.9° of visual angle), and were presented serially in the same spatial locations at a rate of six characters per s, with no inter-stimulus interval. In each sequence, the distractor letters A through K were each presented five times. Targets were not displayed in the first or last 500 ms of the stream, never appeared in pairs, and were separated from one another with a minimum inter-target interval of 1 s. The 1-s interval between target onsets was chosen to ensure that the N2pc and subsequent components triggered by target onsets did not overlap. In the focused-attention conditions (attend left or attend right) 2, 3, or 4 targets were displayed on each side (for a total of 4, 6, or 8 targets). In the divided-attention condition (attend to both sides and respond to targets on both sides) 2, 3, 4, 6, or 8 targets were displayed on each trial. In order to equate stream length across trials, the letter “P” was added to the stream in place of a target as necessary. For the purposes of analysis, the unattended stream of the focused attention condition is referred to as the ignored-attention condition. With the exception of the three-target trials (in which two targets appeared on one side), potential targets were equally divided between the two sides of presentation.

2.1.3. Procedure

Participants first received instructions on how to direct their attention to the left, right or both sides without moving their eyes and to respond as soon as detecting the digit 5 on the side or sides to be attended. A chin rest was used to ensure a constant viewing distance of 60 cm. Before the experimental trials began, each participant practiced the task in the focused-attention condition until a response accuracy criterion of 80% was reached (in general, 15 trials were sufficient to reach the criterion). A trial began with the presentation for 1 s of one or two red (RGB: 127, 0, 0) “arrows” (“<”, “>”, or “<>”) which indicated how attention should be directed (to the left, right, or both sides, respectively). After a 250-ms blank interval, and 750 ms before the presentation of the letter streams, a red fixation cross appeared in the center of the screen and remained on display for the duration of the trial (10 s). Participants pushed any key on the computer keyboard whenever they detected the number “5” on an attended side. Response hand was counterbalanced across participants.

Participants were naive as to the number of targets that would be displayed on each trial. After the presentation of the two sequences of alphanumeric characters, the red fixation cross remained in view for 1 s, after which the trial ended. No performance feedback was given. Eighteen trials were presented for each possible number of targets in each attentional condition resulting in 54 trials for each of the focused and ignored attention conditions (54 focus left - ignore right, 54 focus right - ignore left) and 90 trials for the divided attention condition. The entire experiment lasted approximately 1.5 h.

2.1.4. EEG recording

The EEG was recorded using an electro-cap with 64 tin electrodes. All scalp positions in the International 10-20 System were used, with additional sites located midway between the 10-20 locations and six electrode positions 10% inferior to the standard parieto-occipital electrodes (FT9, PO9, O9, FT10, PO10, O10). Averaged mastoids served as an off-line reference for the EEG signals. An electrode on the sternum was used for the subject ground. To monitor the electrooculogram (EOG), activity was recorded as bipolar input from the left and right horizontal eye channels and from the vertical channels positioned above and below the left eye. Data were recorded at sampling rate of 500 Hz and impedances were kept below 20 kΩ. Electrical activity measured at the electrodes was amplified 20,000 times and digitally filtered using a low-pass FIR filter with a cut-off value of 135 Hz.

2.1.5. ERP data processing

Epochs of 1 s were segmented starting 200 ms before and ending 800 ms after target onset. Only segments corresponding to a correct response (i.e., to a “hit” if the target was to be attended and was responded to or a “correct rejection” if the target was to be ignored and was not responded to) were considered. The EEG channels and the vertical eye-movement channel were screened for artifacts exceeding ± 80 μV of electrode activity. The horizontal eye movement channel was screened for artifacts exceeding ± 30 μV of electrode activity. All epochs in which activity exceeded any of these criteria were excluded from further analysis (an average of 17.5% of segments was removed which, on average, left 182, 237, and 220 epochs for the analysis of the focused-, divided-, and ignored-attention condition respectively). Averaged horizontal eye channel data were visually inspected for activity above 3 μV to check for the possible presence of small but systematic horizontal eye movements. The same procedure was adopted to control for redirection of gaze toward the side to be attended after the onset of the cue. None of the participants included in this dataset performed eye movements above the 3 μV threshold.

The 200-ms interval before target onset served as baseline. Segments were averaged before computing the mean voltage of the ERPs within a specified time window centered on the peak of interest. Grand-average waveforms (see Panel D Figure 1) served as a reference to set the time windows from which each ERP deflection was estimated. The N2pc was computed by averaging waveforms ipsilateral to target presentation across hemispheres and subtracting them from the average of the contralateral waveforms. N2pc amplitude (see Panel D, Figure 1) was estimated by computing the mean activity between 220-320 ms after target onset; the P4pc was estimated by computing the mean activity between 340-430 ms after target onset.

2.2. *Results*

For all ANOVAs of behavioural and EEG data, the Greenhouse-Geisser epsilon correction was used as necessary to adjust degrees of freedom to correct for possible violations of sphericity. For clarity, the unadjusted degrees of freedom are reported.

2.2.1. *Behavioral data*

Responses made within the interval 200-800 ms after target onset were classified as hits. The effect of attention condition (focused vs. divided) on percentage of hits and reaction times was tested with a dependent samples t-test with attention condition as a within-subject factor. The percentage of hits was higher in the focused- (86.2%) than in the divided-attention condition (t(13) = 2.8, p < .016). False alarms to distractors (less than .01% on average) and to-be-ignored-targets (less than .04% on average) were rare. Reaction times to hits were not affected by attentional condition (mean reaction times were 527 and 522 ms for the focused- and divided-attention conditions, respectively, p > .9).

2.2.2. *ERP amplitudes*

Panels A, B, and C of Figure 1 show the grand averages of the contralateral and ipsilateral waveforms for the focused- (Panel A of Figure 1), divided- (Panel B of Figure 1), and ignored-attention conditions (Panel C of Figure 1), and Panel D of Figure 1 shows the differential waveforms (N2pc and P4pc) at the electrodes where the N2pc was maximal (PO7 and PO8). Attentional effects on the N2pc (220-320 ms after target onset) and P4pc (340-430 ms after target onset) amplitudes were tested with a repeated-measures ANOVA with attention condition (focused-, ignored-, or divided-) as a within-subject factor. N2pc amplitude (see Figure 1, Panel D) was affected by attention (F(2, 26) = 22.6, p < .001, MSE = 5.6, η_p^2 = .635). Pairwise comparisons (Bonferroni corrected) revealed that N2pc amplitude was higher in both the focused- and divided-attention conditions than in the ignored-attention condition (ps ¡ .001), but did not differ between the focused- and divided-attention conditions (p > .9). N2pc amplitude in the ignored-attention condition differed significantly from baseline (t(13) = 6.1, p < .001). No effects on peak latency were found.

P4pc amplitude (see Figure 1, Panel D) was also affected by attention condition (F(2, 26) = 8.7, p < .003, MSE = 5, η_p^2 = .4). Pairwise comparisons revealed that P4pc amplitude was higher in the divided- than in either the ignored- (p < .018) or focused-attention condition (p < .004), and did not differ between focused- and ignored-attention conditions (p > .9). P4pc amplitude differed from baseline in both the focused- (t(13) = 4.3, p < .002) and ignored-attention conditions (t(13) = 5.0, p < .001). No effects on peak latency were found.

Scalp topographies of the N2pc and P4pc components are shown in the upper and lower left Panels of Figure 5. Topographies were obtained by mirroring the activity of the N2pc (left Panel) and P4pc (right Panel) across the two hemispheres. Differences in topographies were tested with an ANOVA with attention condition (focused-, divided-, or ignored-), electrodes and components (N2pc or P4pc) as within-subjects factors. Before statistical testing, amplitudes were rescaled using a range normalization procedure (McCarthy & Wood, 1985). The ANOVA yielded main effects of electrode (F(24, 312) = 31.2, p < .001, MSE = 16.6, η_p^2 = .71) and component (F(1, 13) = 24.9, p < .001, MSE = 7.1, η_p^2 = .66). A significant Component x Electrode interaction was obtained (F(24, 312) = 8.4, p < .001, MSE = 3.6, η_p^2 = .4), indicating different topographies for N2pc and P4pc[1] No other effects reached significance.

2.3. *Discussion*

Performance and EEG activity in focused-, divided-, and ignored-attention conditions with multiple targets were compared and in all cases a target-elicited N2pc was followed within about 110 ms by a second component of opposite polarity but similar scalp distribution. N2pc amplitude was higher in the focused- and divided-attention conditions than in the ignored-attention condition, presumably reflecting modulated attentional capture or engagement as a function of instruction. The smaller but significant N2pc for to-be-ignored targets indicates that such targets did capture attention, at least some of the time. Interestingly, such targets failed to elicit a P300, suggesting a dissociation between target selection or attentional capture

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[1] Because the overall differences in scalp topographies might reflect in large part differences at frontal locations, we repeated the same analysis using only the 13 posterior electrodes. This analysis yielded similar results

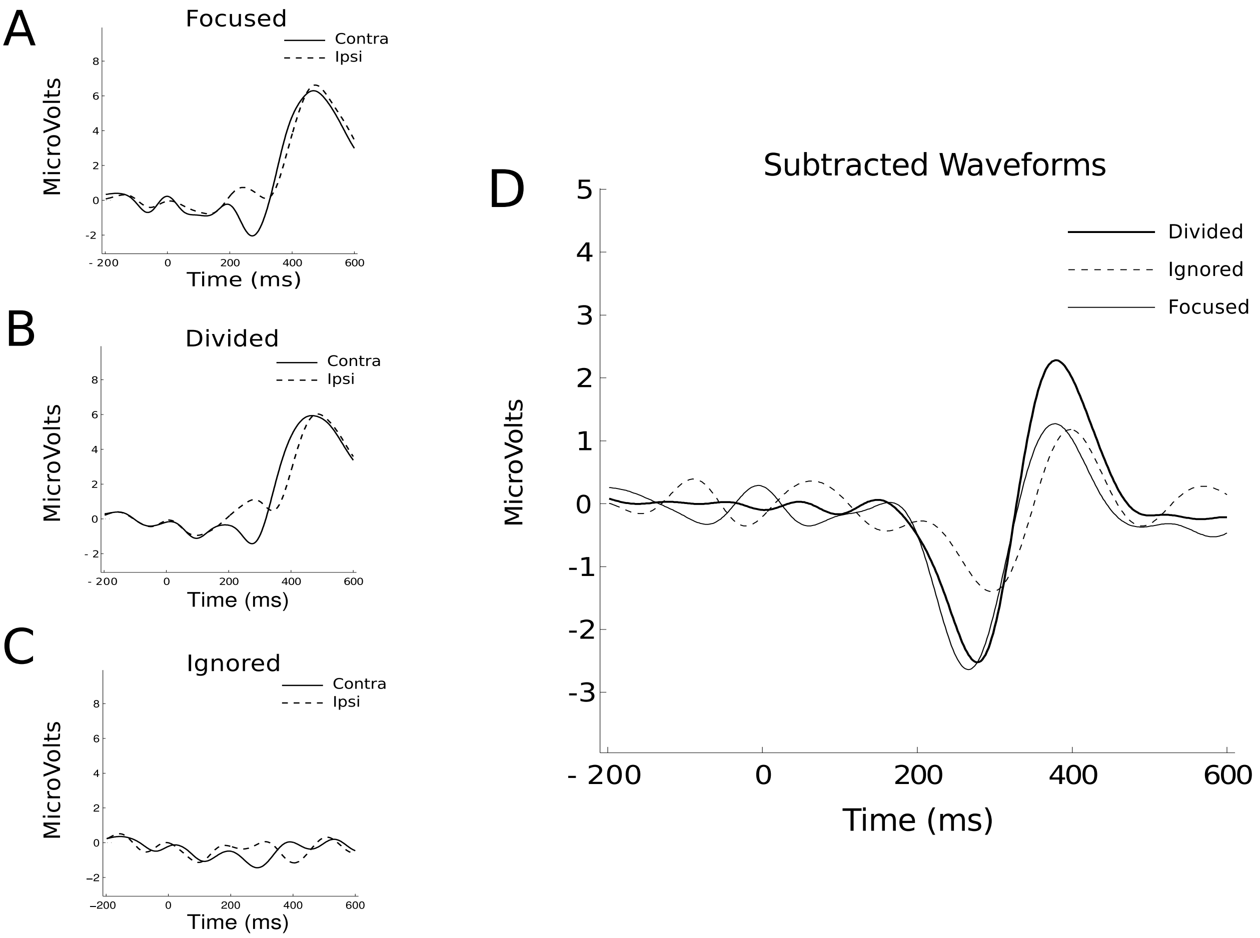

Figure 1: Contra- and ipsi-lateral waveforms at PO7 and PO8 are shown in Panels A, B, and C, for the divided-, focused-, and ignored-attention conditions, respectively. The differential waveforms, the N2pc and the P4pc, at electrodes PO7 and PO8 in the divided-, focused-, and ignored-attention conditions of Experiment 1 are shown in Panel D. For display purposes, N2pc and P4pc were filtered with a second-order (12 dB per octave) low-pass Butterworth filter with a cut-off frequency of 9 Hz.

as reflected by the N2pc and target categorization as reflected by the P300 (see also Luck & Hillyard, 1994). The lack of a difference in N2pc amplitude between the focused- and divided-attention conditions replicates the results of Kiss et al. (2008b), who found no effects of precuing target location on N2pc amplitude. Moreover, it suggests that the degree of target selection or enhancement in the two conditions was comparable. This finding is consistent with the relatively small (albeit significant) difference in detection accuracy and lack of difference in detection latency between the two conditions.

The P4pc showed a pattern of results that contrasts with those found for the N2pc and that seem well in line with the notion that this component reflects attentional disengagement: P4pc amplitude was largest in the divided-attention condition and similar, smaller amplitudes were observed in the focused- and ignored-attention conditions. The finding of a significant P4pc in the focused-attention condition cannot easily be explained in terms of reorienting visuospatial attention in the horizontally opposite direction, and thus provides compelling support for the attentional disengagement hypothesis. The finding of the P4pc in this condition also indicates that attentional disengagement can be purely object based, that is, it can occur without redirection to a different location. A similar conclusion has been drawn with respect to attentional engagement on the basis of N2pc results Kiss et al. (2008b). In conjunction with their highly similar scalp distributions, the object-based nature of the two components supports the notion that they reflect intimately related but functionally opposite processes, that is, the attentional selection of versus the attentional disengagement from lateralized visual targets.

The larger P4pc in the divided-attention condition might reflect stronger/more top-down disengagement in this condition due to the need to restore attention to the divided state. In other words, it may reflect a superposition of a disengagement-related P4pc and a reversed N2pc associated with reorienting spatial attention to fixation or to a divided state. It is also possible that the fact that the average time separating two subsequent targets was shorter in the divided-attention condition than in the other two conditions contributed to this finding. Because lateral shifts of attention were often required, the presence of a P4pc in the divided-attention condition does not by itself constitute compelling evidence for the disengagement hypothesis. The same caveat applies to the sizable P4pc obtained for to-be-ignored targets. Because the N2pc results indicated infrequent or weak attentional capture by such targets, it is possible that the redirecting of attention back to the relevant stream after erroneous capture may have caused the P4pc (i.e., a reversed N2pc), rather than or in addition to attentional disengagement. This issue will be discussed in more detail in the General Discussion.

The fact that the P4pcs found in Experiment 1 were associated with targets embedded in RSVP streams means that the onset of the distractor appearing immediately after the target might have triggered disengagement in a bottom-up, exogenous manner. Thus, it may be that the P4pc will be found only when targets are embedded in RSVP streams or are followed by masks. The absence of masks could explain why there have been many reports of an N2pc in response to a visual-search target without a subsequent P4pc-like component (e.g., Kiss et al., 2008a; Holgun et al., 2009). Also, that using RSVP alone is not sufficient to evoke a P4pc is shown in a study by Dell'Acqua et al. (2006). They used two lateralized RSVP in which a masked second target followed a first one and showed that the second target evoked an N2pc but it was not followed by a P4pc. This suggests that using RSVP alone is not sufficient to evoke a P4pc, but it does not prove that it is not necessary. One aim of Experiment 2 was therefore to investigate whether a P4pc would be found in a visual discrimination task using only a cue frame followed by a search frame.

3. Experiment 2

In Experiment 2 we attempted to establish a direct link between the presence of the P4pc and the need for attentional disengagement using a visual search task with two search frames. The first frame contained a lateralized cue and the second a target (see Figure 2). The disengagement hypothesis was pitted against the reorienting hypothesis by comparing the N2pc and P4pc in three experimental conditions and a control condition. In the experimental conditions, which were blocked, the location of the target was determined by the location of the cue and the instruction condition. In the vertical condition the target appeared in the position above or below the location of the cue, in the horizontal condition the target appeared either to the left or to the right of the cue, and in the stay condition the target appeared in the same position as the cue. Thus, the conditions differed in the nature of the attentional shift from the location of the cue to that of the target: the vertical shift condition required a vertical shift within the same hemifield, the horizontal condition required a shift from the cue in one hemifield to the target in the opposite one, and in the stay condition no shift was required. If the P4pc is largely or exclusively due to a lateral shift of attention, (i.e., if it is a reversed N2pc), it should be apparent only in the horizontal-shift condition, as this is the only condition for which a lateral shift of attention is required and thus the only condition for which a post-cue N2pc should be evoked (Woodman & Luck, 1999, 2003; Hickey et al., 2006). If, on the other hand, the P4pc predominantly reflects attentional disengagement, it should be present—and its amplitude should be similar—across the three conditions. The control condition consisted of trials in which the cue was never followed by a target. Because no attentional disengagement from the cue is required when there is no subsequent target, no P4pc should be found in this condition.

3.1. *Material and Methods*

3.1.1. *Participants*

Eighteen healthy individuals participated in the experiment. One participant was excluded because of poor performance, and four other participants were excluded because they failed to keep their eyes at fixation in the interval between the first and the second search arrays. The remaining thirteen participants (4 males) age range 18 to 21, (mean age = 19.8 years, s.d. = 1) were included in all further analyses. The study adhered to the Declaration of Helsinki and was approved by the local ethics committee. Informed consent was obtained from all participants.

3.1.2. *Stimuli and apparatus*

Stimuli were presented on a 17" CRT monitor (800 x 600 pixels at 100-Hz) positioned at 65 cm in front of the participants. A central red fixation cross was displayed for the duration of the block. Search arrays contained eight stimuli presented at the eight positions located on an imaginary square rotated by 45° (see Figure 2). The items in the search arrays were light gray (RGB: 204, 204, 204) presented against a uniform black background (RGB: 0, 0, 0). Each item subtended a visual angle of 1°.

In the first search array (the cue frame) distractors were squares and the cue was a diamond (a square rotated by 45°) and in the second search array (the target frame) distractors were diamonds and the target was a truncated diamond. Six possible targets were created by truncating one side of the diamond by 5", 10", or 15" of visual angle and the corresponding side by 10", 15", or 20" of visual angle, respectively, thereby keeping the difference in length of the two truncated sides constant. The target search array was followed by a third array (the mask) consisting of eight figures made by merging a square and a diamond. Participants were to respond by pushing the 'd' key of the computer keyboard with the index finger of the left hand if the truncated diamond appeared more truncated on the left than on the right side or the 'j' key with the index finger of the right hand if it appeared more truncated on the right than on the left side.

The cue and target could appear only in the positions closest to fixation (on screen this corresponded to a distance of 4.5° vi-

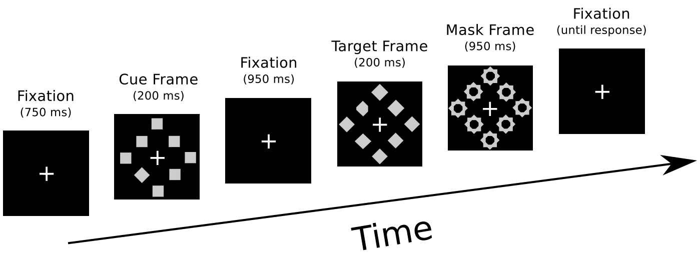

Figure 2: Schematic of a vertical-shift trial of Experiment 2. In this trial the diamond in the cue frame appeared 750 ms after the beginning of the trial and remained in view for 200 ms. The diamond indicated that the truncated diamond (the target) would appear in the position above the diamond after 950 ms. The target frame was then displayed for 200 ms and replaced by a mask for 50 ms. The next trial started as soon as the response was emitted.

sual angle from the fixation cross). The location of the cue was chosen randomly with the restriction that all four positions were used equally often. The location of the target was determined by the location of the cue and the instruction condition. In the vertical condition the target appeared in the position above or below the location of the cue, in the horizontal condition the target appeared either to the left or to the right of the cue, and in the stay condition the target appeared in the same position as the cue. In a fourth, "no cue" condition, the "cue" frame was composed of squares only and therefore provided no information about the position of the truncated diamond in the target frame.

3.1.3. Procedure

Participants first performed 48 practice trials in which only the target frame was displayed, followed by two practice blocks of 48 trials each in which the mask frame followed the target frame. Participants were then instructed how to perform the task. They first received instructions on how to direct their attention to the left, right, up or down without moving their eyes from fixation, and to blink their eyes only immediately after emitting responses. Participants were also told that the discrimination of the truncated diamond in the target frame would be easier if they used the information provided by the cue. Before the start of the experimental session, 48 trials of practice with each cue type (horizontal, vertical, stay, or none) were given.

The experimental session consisted of 17 blocks with 48 trials each. Fifteen of these blocks were five repetitions of the three experimental blocks (vertical, horizontal, or stay cue) in which the position of the cue predicted the position of the target. These 15 blocks were presented in random order. One no-cue block was presented as the first block in the experimental session and the other as the last.

A trial started with the presentation for 750 ms of a red (RGB: 127, 0, 0) fixation cross. The cue frame was then displayed for 200 ms; 950 ms after the cue offset the target frame was displayed for 200 ms and was immediately followed by the mask frame for 50 ms. The following trial started after the participant's response. Breaks of 5 seconds, or longer if desired, were allowed after the 16th and 32nd trials.

An additional control session, consisting of one practice block of 48 trials and two blocks of 144 trials each, was conducted after the experimental session. In this session, only the cue frame was displayed and participants were to respond by pushing the 'd' key of the computer keyboard with the index finger of the left hand if the diamond appeared on the left side of the display or the 'j' key with the index finger of the right hand if the diamond appeared on the right. Participants were allowed to take breaks after the 48th and 96th trials.

Trials in the control session started as did the trials in the experimental session, with the presentation of the fixation cross for 750 ms followed by the presentation of the cue frame for 200 ms. The following trial would start after 1.25 s, during which participants had to make a response. Such relatively long inter-target interval (2.2 s) was used to diminish the chance that participants would feel pressure to disengage from the current target to process the forthcoming one. The entire experiment (practice, experimental, and control session) lasted approximately 2 h.

3.1.4. EEG recording

The EEG was recorded as in the previous experiment.

3.1.5. ERP data processing

Epochs of 1 s were segmented starting 250 ms before and ending 750 ms after cue onset. The EEG channels and the vertical eye-movement channel were screened for artifacts exceeding ± 80 μV of electrode activity. The horizontal eye movement channels was screened for artifacts exceeding ± 30 μV of electrode activity. All epochs in which activity exceeded any of these criteria were excluded from further analysis (an average of 10.25% of segments was removed which, on average, left 224, 215, and 220 epochs for analysis for the vertical, horizontal, and stay conditions, respectively). ERPs were visually inspected on the averaged horizontal and vertical eye channel data for activity above 3 μV to check for the possible presence of small but systematic eye movements. The same procedure was adopted to control for redirection of gaze toward the side to be attended after the onset of the cue. None of the participants included in the analyses performed eye movements above the 3 μV threshold.

The 200-ms interval before cue onset served as baseline. Segments were averaged before computing the mean voltage of the ERPs within a specified time window centered on the peak of interest. Grand-average waveforms (see Figure 4, Panel E) served as a reference to set the time windows from which each ERP deflection was estimated. The N2pc was computed by averaging waveforms ipsilateral to cue presentation across hemispheres and subtracting them from the average of the contralateral waveforms. N2pc amplitude (see Figure 4, Panel E) was estimated by computing the mean activity between 220-300 ms after target onset; the P4pc was estimated by computing the mean activity between 315-375 ms after cue onset.

3.2. Results

For all ANOVAs of behavioural and EEG data, the Greenhouse-Geisser epsilon correction was used as necessary to adjust degrees of freedom to correct for possible violations of sphericity. For clarity, the unadjusted degrees of freedom are reported.

3.2.1. Behavioral data

Proportion of correct responses and the reaction times in the experimental session are shown in Figure 3. Accuracy and reaction time in the no-cue condition was compared with average performance in the three instruction conditions (horizontal, vertical, or stay) using t-tests. The proportion of correct responses was higher in the cue conditions (.90) than in the no-cue condition (.73), $t(1, 12) = 7.6$, $p < .001$. Reaction times were faster in the cue conditions (613 ms) than in the no-cue condition (731 ms), $t(1, 12) = -5.9$, $p < .001$.

The effects of instruction condition (horizontal, vertical, or stay) on the proportion of correct responses and on the reaction

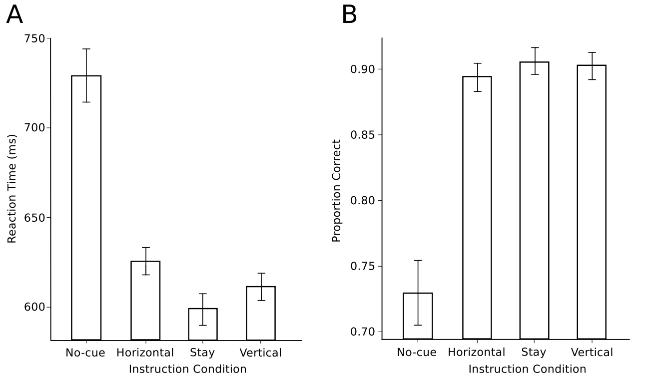

Figure 3: Reaction times (Panel A) and proportion of correct responses (Panel B) for the no-cue, stay, vertical, and horizontal conditions of Experiment 2, respectively. Error bars are 95% confidence intervals.

times in the experimental session was tested with a repeated measures ANOVA. Only responses between 200 and 1000 ms after target onset were considered in this analysis. There were no significant effects of instruction condition on the proportion of correct responses. However, instruction condition affected the reaction times (F(2, 24) = 6.18, p < .010 MSE = .011, η_p^2 = .34). Pairwise comparisons (Bonferroni corrected) revealed that reaction times were faster in the stay condition (600 ms) than in the horizontal condition (627 ms; p < .02), whereas discrimination speed did not statistically differ between the vertical (613 ms) and stay (p > .1) conditions or between the vertical and horizontal (p > .1) conditions. The proportion of correct responses in the control session was .98 and the mean reaction time was 485 ms.

3.2.2. ERP amplitudes

Panel A, B, and C of Figure 4 shows the grand averages of the contralateral and ipsilateral waveforms for the vertical-,horizontal-, and stay-instruction conditions of the experimental session respectively. Contra and ipsilateral waveforms of the control session are shown in Panel D of Figure 4. Panel E of Figure 4 shows the differential waveforms (N2pc and P4pc) at the electrodes where the N2pc was maximal (PO7 and PO8). Instruction effects on the N2pc (220-300 ms after target onset) and P4pc (315-375 ms after target onset) amplitudes were tested with a repeated-measures ANOVA with instruction condition (vertical, horizontal, or stay) as a within-subjects factor.

N2pc amplitude (see Panel E of Figure 4) was not significantly affected by instruction condition (p > .3). N2pc amplitude differed from baseline in the vertical (t(12) = -3.1, p < .009), horizontal (t(12) = -4.8, p < .001), and stay conditions (t(12) = -4.1, p < .001). P4pc amplitude (see Panel E of Figure 4) was also not affected by instruction condition (p > .5). P4pc amplitude differed from baseline in the vertical (t(12) = 3.8, p < .003), horizontal (t(12) = 4.7, p < .002), and stay conditions (t(12) = 4.2, p < .002). Given the absence of statistical differences between the three instruction conditions, ERP amplitudes were averaged across instruction conditions in the experimental session to be compared with the N2pc and P4pc amplitudes computed in the control session. Paired samples t-tests revealed that N2pc amplitude was higher in the control than in the experimental session (t(12) = 5.9, p < .001), but that P4pc amplitude was higher in the experimental than in the control session (t(12) = 2.7, p < .02). Whether N2pc and P4pc components were present in the control session was tested with paired samples t-tests against the baseline. Whereas am-

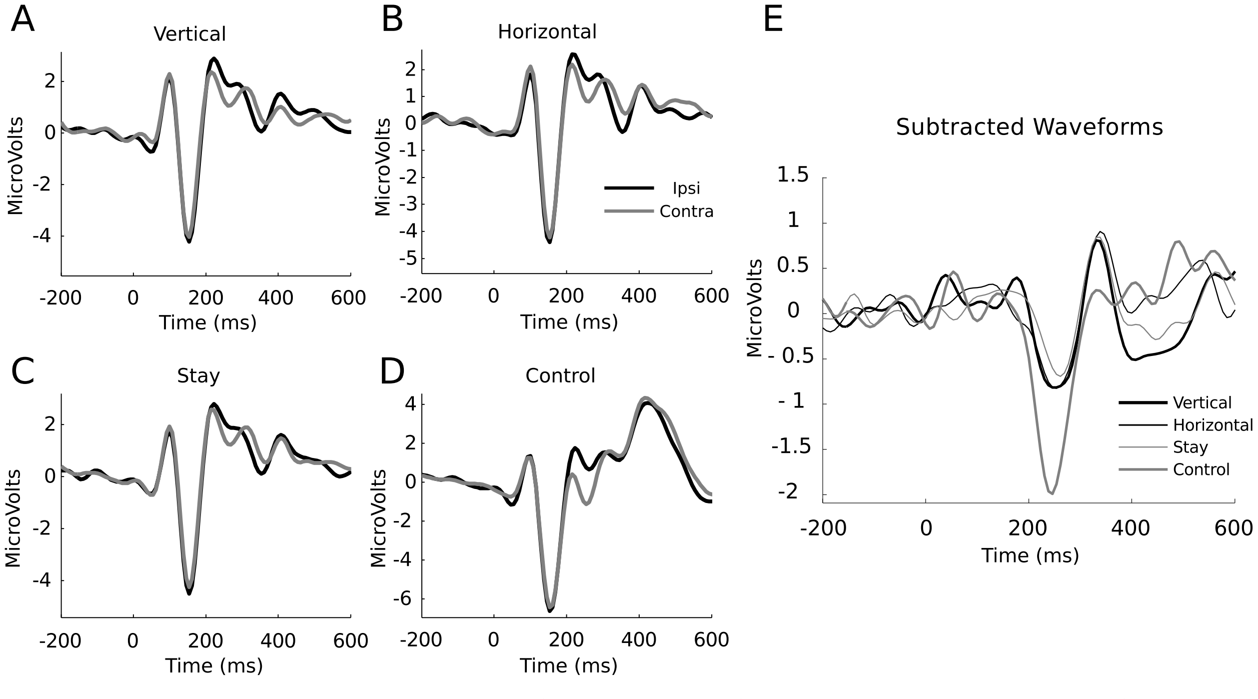

Figure 4: Panels A, B, C, and D show the contra- and ipsi-lateral waveforms at PO7 and PO8 for the experimental and control conditions of Experiment 2. Panel A shows the horizontal trials, Panel B the vertical trials, Panel C the stay trials, and Panel D the control session. Panel E depicts the differential waveforms, the N2pc and the P4pc, at electrodes PO7 and PO8 for the horizontal, vertical, stay, and control trials. For display purposes, N2pc and P4pc were filtered with a fourth-order (24 dB per octave) low-pass Butterworth filter with a cut-off frequency of 15 Hz.

plitude of the N2pc was significantly different from the baseline (t(12) = -7.3, $p < .001$), P4pc amplitude did not significantly differ from the baseline (t(12) = -.5, $p > .6$)

Scalp topographies of the N2pc and P4pc components for the vertical, horizontal, and stay instruction condition of the experimental session and for the control session are shown in the right Panels of Figure 5. Topographies were obtained by mirroring the activity of the N2pc (upper left Panels of Figure 5) and P4pc (lower left Panels of Figure 5) across the two hemispheres. Differences in N2pc topographies were first tested with an ANOVA with session (vertical, horizontal, or stay instruction condition, and control session) and electrodes as within-subjects factors. Before statistical testing, amplitudes were rescaled using a range normalization procedure (McCarthy & Wood, 1985). The ANOVA yielded a main effect of electrode (F(25, 300) = 18.1, $p < .001$, MSE = 7.9, $\eta_p^2 = .60$). No other effects reached significance[1]. The absence of a significant Session x Electrode interaction indicates that the N2pc topographies were not significantly different across the two sessions.

Differences between N2pc and P4pc scalp topographies were tested with an ANOVA with instruction condition (vertical, horizontal, or stay), electrodes, and components (N2pc vs. P4pc) as within-subjects factors. The ANOVA yielded a main effect of electrode (F(25, 300) = 35.6, $p < .001$, MSE = 11.5, $\eta_p^2 = .75$). No other effects reached significance[1].

3.3. Discussion

The comparison of ERPs to a cue when followed by a target at the same location, on the same side of the display but above or below the cue, on the other side of display but at the same position in the vertical plane as the cue, or by no target at all yielded two important results. First, a P4pc was found following the initial N2pc, but only when the cue was known to be followed by a target. Second, the amplitude of the P4pc was no different when the spatial shift from the cue to the target was in a horizontal direction—and potentially could have caused a reversed N2pc—as compared to when it was in a vertical direction or when the cue and target shared the same location—which in neither case would result in a reversed N2pc.

Our findings linking the P4pc to attentional disengagement from lateralized targets also suggest that such disengagement can be characterized as proactive and endogenously controlled. Because the cue was not masked and the P4pc occurred long (in electrophysiological terms) before the target was presented, it cannot be argued that the target or a mask triggered disengagement. It might be argued that, because the cue was presented for only 200 ms, its offset may have triggered attentional disengagement. However, the fact that no P4pc was found in the control condition in which the cue also was presented for 200 ms argues against this and suggests that even if disengagement is linked to target offset, it is subject to top-down control (for similar arguments regarding attentional capture by stimulus onsets, see Akyrek et al., 2010a; Kiss et al., 2008a; Holgun et al., 2009).

N2pc amplitude was substantially larger in the control condition, in which only the cue was presented and required an explicit response, than in the experimental conditions in which the cue was not responded to. This result was not anticipated and is open to different interpretations. For example, the fact that the horizontal location of the target had to be responded to in the control condition may have sensitized the processing system to the horizontal spatial dimension (i.e., this may have made the horizontal dimension more salient), thus enhancing differential

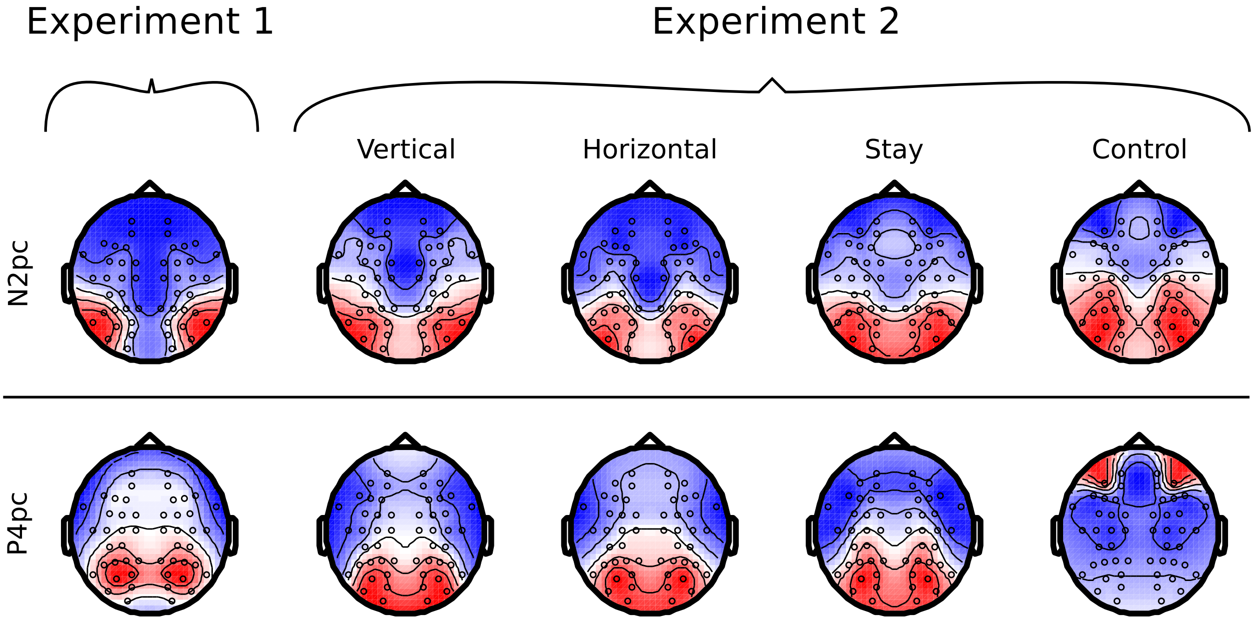

Figure 5: Rescaled topographies of the N2pc and P4pc in the two experiments. For Experiment 1 only topographies in the divided-attention condition are shown because the focused- and ignored-attention conditions were very similar. For Experiment 2 the topographies in the (horizontal, vertical, and stay) and control conditions are shown. Note that to aid comparison of the N2pc and P4pc topographic maps, the polarity of the P4pc has been inverted. Moreover, note that blink activity is present in the P4pc's time range for the control condition in Experiment 2. This is because participants were instructed to blink immediately after the responses, which in this condition was after the cue frame.

processing of the horizontally lateralized stimuli. Alternatively, the smaller amplitude of the N2pc in the experimental conditions may reflect the interruption or curtailment of attentional capture or engagement by the functionally opposite process of disengagement, or joint preparation of initial engagement to be followed by disengagement. Advance preparation of engagement followed by disengagement may have weakened the nature or quality of preparation for the initial engagement step compared to when engagement was only step, just as the speed and efficiency of the first movement in a series is negatively affected by the length of the series (Schneider & Logan, 2007).

4. General Discussion

The present experiments were conducted to determine if a component following the N2pc, but of opposite polarity might reflect the process of attentional disengagement from a lateralized visual target. In Experiment 1, the requirement to process multiple, successive targets in lateralized RSVP streams was shown to evoke a disengagement-related ERP component (which we call the P4pc). In Experiment 2, the results of a cued visual-search task provided evidence that the disengagement processes reflected by the P4pc are not driven in a bottom-up manner by the presence of a mask following the target and to showed that the P4pc does not represent a reversed N2pc resulting from a redistribution of attention back to fixation after processing of a lateralized target.

The main contribution of the present paper is the demonstration that a novel N2pc-related component, the P4pc, can reflect disengagement of attention from lateralized visual objects or locations. The P4pc in the present studies did not require or depend on a horizontal shift of attention back to center or to the opposite hemifield, did not require a mask terminating target presentation, and was not automatically triggered by target offset, but did critically depend on a task-imposed need for disengagement. Based on this evidence, we suggest that the P4pc is correlated with disengagement of attention, and that such disengagement can be endogenously triggered.

A possible alternative interpretation of the P4pc is that it may reflect merely latency and/or amplitude differences in ipsi- and contralateral P300. However, the scalp distributions of the P4pcs in the present study were markedly different from, and more posterior than, that of the P300. Also, a clear P4pc but no P300 was present for targets in the to-be-ignored stream of the focused-attention condition of Experiment 1. The P4pc thus seems to constitute a genuine component related to attentional processing.

Our interpretation of the P4pc reported in Experiment 1 hinges on the assumption that participants followed instructions in the focused-attention condition. If, on the other hand, attention was sometimes divided across the streams, the evidence for attentional capture by targets in the to-be-ignored stream might not reflect infrequent, involuntary, and erroneous capture, but rather the use of a divided-attention strategy on a subset of trials in the focused-attention condition. In conjunction with the alternative interpretation of the P4pc as a reversed N2pc, this could explain the pattern of P4pc (cq, reversed N2pc) amplitudes across conditions. The larger P4pc in the divided-attention condition would reflect the redistribution of attention to a divided state that is necessary on all trials, whereas the smaller but similar P4pcs for to-be-attended and to-be-ignored targets in the focused-attention condition would reflect such a redistribution on only the subset of trials in which a divided-attention strategy was used.

Similarly, if in Experiment 2 participants failed to direct attention to the known location of the upcoming target on a subset of trials and instead redirected it back to fixation or to a more diffuse attentional state, a reversed N2pc could result. However, P4pc amplitude was no different in the horizontal-shift condition than in the other experimental conditions, which could only occur if failures to focus attention on the known location of the target occurred on the majority of trials. This is clearly ruled out by the behavioral results. Accuracy of target discrimination was only 70% in the no-cue condition, in which advance focusing on the location of the target was impossible, and accuracies in the three cued conditions were well over 90%, indicating that advance location information was effectively and consistently used.

The P4pc component might also be described as a reversed N2pc associated with the re-allocation of attention to a target which had previously been attended to or which is anticipated to be relevant in the next situation – irrespective of whether such re-allocation involves a spatial shift of attention. Whereas the disengagement hypothesis links the P4pc to the de-allocation of attention from the first target, this proposed alternative links it to the re-allocation to the subsequent target[2]. While this proposal may have some merit, it would seem to predict–contrary to what we observed in Experiment 2–that the N2pc associated with such re-allocation would have the same polarity as the initial N2pc when the second target is known or expected to be located at the same position or in the same left/right hemifield as the first target.

Although we found compelling evidence linking the P4pc and endogenous disengagement, the P4pc, or something looking like it, may also occur in other circumstances. Brisson and Jolicoeur (2007a, Experiment 1, 2007b), for example, found a P4pc-like component in an auditory-visual psychological refractory period (PRP) paradigm when the search display for the visual task was masked after 133 ms (Brisson & Jolicoeur, 2007a) but not when it was not (Brisson & Jolicoeur, 2007b). Because the mask was symmetric across both visual fields, the observed P4pc-like component cannot have reflected lateralized brain activity evoked in a bottom-up manner by the mask itself. Rather, it seems that the mask effectively interrupted or terminated visual processing, and in that way triggered attentional disengagement. Although the authors themselves did not comment on the presence or absence of the P4pc-like component, their results seem consistent with the idea that the P4pc reflects the process of attentional disengagement, or its outcome, irrespective of whether the process is triggered exogenously, endogenously, or both.

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[2] We thank an anonymous reviewer for pointing out this possibility.

In hindsight, many N2pc studies seem to have yielded P4pc-like components (see, e.g., Akyrek et al., 2010a; Brisson & Jolicoeur, 2007a; Eimer et al., 2009; Girelli & Luck, 1997; Leblanc et al., 2008; Lien et al., 2008; Seiss et al., 2009; Woodman & Luck, 1999, 2003). However, few authors (Eimer & Kiss, 2008; Lien et al., 2008; Seiss et al., 2009; Woodman & Luck, 1999, 2003) have acknowledged the presence of such components or attempted to account for them, and these accounts have usually been in terms of a reversed N2pc that reflects a reverse horizontal attentional shift or the attentional selection of an object in the opposite visual field. Close scrutiny of these studies suggests that in some cases the P4pc-like component is unlikely to indicate attentional disengagement. For example, Akyrek et al. (2010b) used a visual search task in which a pop-out target occurred on a portion of trials, and showed that a P4pc-like component follows the N2pc to these targets. It should be noted that because target duration in at least one experiment (Akyrek et al., 2010a, Experiment 2) was 500 ms, target offset or onset of the subsequent mask cannot have triggered the P4pc-like component. Also, inter-trial intervals in at least some of Aky*ü*rek et al.'s experiments were sufficiently long to obviate any reasonable need for rapid disengagement. It is not clear what aspect of the nature of the visual displays or the experimental procedure used in these studies was responsible for the observed P4pc-like component, even more so as no such component was obtained in another recent N2pc study that used very similar displays and procedures (Holgun et al., 2009). Examples such as this suggest caution in uncritically inferring the operation of attentional disengagement from the presence of P4pc-like components, and indicate a need for further research to determine more precisely under which conditions such an inference is justified.

Modern theories and models of visual search typically deal with successful searches and target-present responses, but, with the possible exception of highly constrained and repetitive search tasks (e.g. Chun & Wolfe, 1996), fail to address the question of how and when an unsuccessful search is abandoned (Herd & O'Reilly, 2005). In real-life, complex visual environments must be scanned, multiple decisions to terminate search at the currently attended part of the visual field and to move on to another area must be made, and search often terminates with the decision to abandon the search altogether. As put by Wolfe & Horowitz (2008), "It is daunting to contemplate how unsuccessful searches are terminated under real-world conditions" (p. 8). The P4pc holds promise as a tool for studying attentional disengagement and may enhance and enrich our understanding of the strategies and dynamics of visual attention and visual search.

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