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Visual search is postponed during the period of the AB: an event-related potential study

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Abstract

In the phenomenon known as the *attentional blink* (AB), perception of the second of two rapidly sequential targets (T2) is impaired when presented shortly after the first (T1). Studies in which T2 consisted of a pop-out search array provided evidence suggesting that visual search is postponed during the AB. In the present work, we used behavioural and electrophysiological measures to test this postponement hypothesis. The behavioural measure was reaction time (RT) to T2; the electrophysiological measure was the onset latency of an event-related-potential index of attentional selection, known as the N2pc. Consistent with the postponement hypothesis, both measures were delayed during the AB. The delay in N2pc was substantially shorter than that in RT, pointing to multiple sources of delay in the chain of processing events, as distinct from the single source postulated in current theories of the AB. Finally, the finding that the N2pc was delayed during the AB strongly suggests that attention is involved in the processing of pop-out search arrays.

The human visual system is severely limited in its ability to process rapidly-changing visual stimuli. This limitation has been studied with a phenomenon called the *attentional blink (AB)* in which perception of the second of two targets is impaired when the temporal lag between them is shorter than about 500 ms (Raymond, Shapiro, & Arnell, 1992). Accounts of the AB differ, but it is generally agreed that the second-target deficit occurs because of attentional constraints arising from the requirement to process the first target.

In the conventional AB paradigm, two targets (T1 and T2; e.g., two letters) are inserted in a stream of distractors (e.g., digits) displayed in rapid serial visual presentation (RSVP). In a variant of this paradigm, T1 is still embedded in an RSVP stream of distractors, but T2 involves a visual search in which the target is an oddball (e.g., a tilted line segment) presented within an array of distractors (e.g., line segments oriented orthogonally to the target). Observers report the presence/absence of the oddball. There are two indices of performance in such search tasks: (a) response time (RT) and/or accuracy, and (b) efficiency, as indexed by the slope of the function relating RT to the number of items in the search array (set size): the shallower the slope, the more efficient the search. Both RT and accuracy have been found to be impaired during the period of the AB (Ghorashi, Smilek, & Di Lollo, 2007; Joseph, Chun, & Nakayama, 1997). Surprisingly, however, Ghorashi et al. found search efficiency to be entirely unaffected. Namely, the slope of the search function was invariant with inter-target lag. This slope invariance led Ghorashi et al. to conclude that visual search is postponed during the period of the AB until processing of T1has been completed. During the postponement, the internal representation of the search array (T2) was said to be stored in a preattentive buffer. Once attentional resources were again available for T2, the search task could be performed efficiently as though there had been no delay.

Electrophysiological Investigations of Visual Search during the AB

The main objective of the present study was to examine this postponement hypothesis by means of electrophysiological recordings. We used a component of the event-related potential (ERP), the N2pc, which is a negative deflection in the ERP waveform that occurs 200-300 ms post stimulus over posterior scalp regions contralateral to the target. The latency of the N2pc is thought to index the time at which selective attention is deployed to the target (e.g., Eimer, Kiss, & Cheung, 2010; Dowdall, Luczak, & Tata, 2012). We reasoned that if the search task – and hence the deployment of attention to T2 – is postponed during the period of the AB, the postponement should be reflected in the latency of the N2pc.

The relationship between T2-processing and the N2pc has been examined in a number of earlier studies (Akyürek, Leszczyński, & Schubö, 2010; Brisson & Jolicœur, 2007; Corriveau et al., 2012; Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, b; Lien, Croswaite, & Ruthruff, 2011; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 2007; Verleger, Śmigasiewicz, Michael, & Niedeggen, 2012). The main consideration for the present work, however, is that the paradigms employed in these studies are not directly comparable to the oddball paradigm employed by Ghorashi et al. (2007). Notably, with the two exceptions noted below, the T2 stimulus employed in these studies was not a conventional search array as used by Ghorashi et al. Mainly for this reason, those earlier studies cannot be used to assess Ghorashi et al.'s hypothesis that visual search is postponed during the period of the AB.

The two exceptions are the studies of Corriveau et al. (2012), and Lien et al. (2011) in which the T2 stimulus consisted of a search array. The usefulness of these two studies for evaluating Ghorashi et al.'s (2007) search-postponement hypothesis, however, is constrained by procedural differences. Corriveau et al. employed a compound search task in which the target location within the search array was demarcated by a salient place-holder that contained the target to be identified. A similar compound-search task was used by Lien et al. An important consideration is that, in both those studies, the process of identifying the target consisted of two steps: target localization and target identification, thus involving a task switch within the T2 task (Enns, Visser, Kawahara, & Di Lollo, 2001). What renders the outcomes of these two studies unsuitable for evaluating Ghorashi et al.'s search-postponement hypothesis is that the N2pc could not be attributed unambiguously to the process of searching for the target location (e.g., Eimer et al., 2010; Dowdall et al., 2012) or to the process of identifying the target itself (e.g., Hickey, Di Lollo, & McDonald, 2009). In addition, both Corriveau et al. and Lien et al. employed a paradigm known as Psychological Refractory Period in which observers made speeded responses to both targets. Executing a speeded response to the first target could affect T2 processing – and hence the N2pc triggered by T2 – in ways that might prejudice comparison with the Ghorashi et al. experiments.

Equivalence of the pop-out and the compound search paradigms with respect to the latency and amplitude of the N2pc cannot merely be assumed. There are no studies in which the N2pc obtained with a pop-out search task was compared directly with the N2pc obtained with a compound search task. Furthermore, even if it were the case that the pop-out and the compound search paradigms triggered equivalent N2pc components, it is still not known whether the results obtained with the two paradigms are affected in different ways during the period of the AB. Similar considerations apply for the N2pc obtained with the PRP and the AB paradigms. A case has been made for the AB to be regarded as a special case of the PRP (Jolicœur, 1999). But, there are no studies in which the N2pc component obtained with the two paradigms have been compared directly. Thus, it cannot be assumed that the latency and amplitude of the N2pc –

which in the present study is used as an index of search postponement – is invariant with the experimental paradigm.

The Present Study

In the present study, the T1 task was to indicate the parity of a digit presented in an RSVP stream of letter distractors. The T2 task was to detect the presence/absence of a colour oddball in an otherwise uniformly-coloured search array. On the twin assumptions that (a) the latency of the N2pc is an index of attentional deployment, and (b) the search task is postponed during the period of the AB, the latency of the N2pc to the T2 oddball should be longer when the inter-target lag is short than when it is long. This is because at short lags the T2 search task is performed during the period of the AB and is, therefore, postponed until T1-processing has been completed, with a consequent delay in the N2pc elicited by T2. In contrast, at the longer lags, the T2 search task is performed outside the period of the AB, namely, after T1 has been processed. In this case, no delay in T2 processing – and hence no delay in the N2pc – is to be expected. The present study was a test of this expectation.

Method

Participants

Seventeen paid observers took part in this experiment. Three were excluded because of excessive eye movements and blinks, resulting in less than 50% of trials after artefact correction. The remaining fourteen participants (six female, two left handed, aged 26-46 years; mean age 32.5 years) all had self-reported normal or corrected-to-normal vision.

Apparatus and Stimuli

Stimuli were presented on a 22” Samsung wide SyncMaster 2233 LCD monitor with a refresh rate of 100 Hz. The stimuli consisted of digits and uppercase letters presented in gray

(CIE color coordinates .324/.348) and red and green coloured rings (red .09/.338; green .262/.558). All stimuli were equiluminant at 12 cd/m^2 and were presented against a black background. The alphanumeric characters subtended 0.8 degrees of visual angle vertically. Each ring subtended 0.8 × 0.6 degrees of visual angle and were arranged in a search array consisting of six rings positioned at equidistant points along the circumference of an imaginary circle of 6.8 degrees radius, centered at fixation. The rings were all lateralized relative to the vertical midline, corresponding to the 1, 3, 5, 7, 9, and 11 o'clock positions on a clock face. Four custom response-buttons were positioned on the desk such that button-press responses could be made with the index and middle fingers of both hands.

Procedure

An example of the display sequence is presented in Figure 1. All displays were viewed from a distance of one meter. At the beginning of each trial, a fixation cross was presented in the center of the screen for 400 ms followed by a blank screen for 200-600 ms prior to the appearance of the first item in an RSVP stream. The RSVP consisted of a sequence of grey-letter distractors presented in the center of the screen. The letters were drawn randomly without replacement from the English alphabet (except I, O, and Q). Each letter was displayed for 50 ms and was separated from the next letter by an inter-stimulus interval of 50 ms, during which the display was blank. Thus, the stimulus-onset asynchrony (SOA) between successive items in the RSVP stream was 100 ms.

----- insert Figure 1 about here -----

The first target (T1) was a digit (2-9, inclusive) inserted in the RSVP stream, and it was preceded by between 5 and 8 letter distractors at random. The second target (T2) was a search display, presented for 150 ms, comprising six colored rings. On one third of the trials, all rings were the same color (all red or all green); on the remaining two thirds of the trials, the search display contained one colour-oddball (one red ring amongst five green rings, or one green ring amongst five red rings). There were three intertarget lags. At Lag 0, the onset of T2 was simultaneous with that of T1. At Lags 2 and 7, the onset of T1 preceded that of T2 by 200 ms and 700 ms, respectively. The RSVP stream continued to be displayed during both the intertarget interval and the 150 ms duration of the search display, such that two RSVP items appeared while the search display was on view. After the search display had been presented for 150 ms, the screen went blank.

Participants performed two tasks on each trial. They were instructed to first respond as quickly as possible to the presence or absence of the oddball in the T2 search display. Responses were made using the index or middle finger of the assigned hand for an oddball-present or oddball-absent response, respectively. Upon making a response to the T2 stimulus, a prompt was displayed on the screen asking participants to identify the parity of T1 (i.e., whether the digit was even or odd) at their leisure. With the hand not used for the T2 task, participants responded with either the index or middle finger for odd or even, respectively. An even/odd response was used as the T1 task because it permitted the observers to position their fingers on the appropriate response buttons. The alternative of using a digit-identification T1 task may have introduced muscle- and eye-movement artifacts caused by searching for appropriate button on the keyboard. The hands used for the T1 and T2 tasks were counterbalanced across participants. After the two responses were made, the next trial was initiated automatically.

Each participant performed fifteen blocks of 54 trials, each counterbalanced for presence or absence of the T2 oddball, side of the T2 oddball (left or right visual field), colour of the rings in the search array, and inter-target lag. One practice block preceded the experimental blocks. Feedback on performance (T1, T2, and overall accuracy) was provided after each block.

EEG Recording and Data Analysis

The continuous EEG was DC-recorded at 23 electrode sites at standard positions of the extended 10/20 system (Fpz, Fz, F3, F4, F7, F8, FC5, FC6, Cz, C3, C4, T7, T8, CP5, CP6, Pz, P3, P4, P7, P8, PO7, PO8, Oz) and sampled at a rate of 500 Hz. The EEG was digitally low-pass filtered at 40 Hz, and no other filters were applied offline. All electrodes were referenced online to the left earlobe, and were re-referenced offline to the average of both earlobes. The EEG was epoched into segments of 600 ms, ranging from 100 ms before to 500 ms after T2 onset. The segmented EEG was baseline corrected with respect to the 100-ms pre-stimulus time window. Trials contaminated with artifacts (HEOG exceeding +/- 30 µV; VEOG at Fpz exceeding +/- 60 µV; activity on all other electrodes exceeding +/- 80 µV), or with incorrect or missing responses to one or both targets were excluded from all analyses. The artefact rejection led to an exclusion of 2.7% of all trials in the Lag 0 condition, of 3.5% of all trials in the Lag 2 condition, and of 3.2% of all trials in the Lag 7 condition. In addition, oddball-absent trials were excluded from all analyses because the ERP component of interest (N2pc) can be observed only on trials on which there is a lateralized target, such as an oddball. EEG was averaged for all combinations of T1-T2 Lag (0, 2, 7) and laterality (electrode PO7/8 ipsilateral or contralateral to the location of the T2 oddball).

N2pc components to oddballs in the T2 visual search array were quantified on the basis of mean amplitudes obtained in a 240-320 ms time window after T2 onset at lateral posterior electrodes PO7 and PO8 at which the amplitude of the N2pc was maximal. Jack-knifed N2pc onset latencies were determined on the basis of grand-averaged difference waveforms, obtained by subtracting ipsi- from contralateral ERPs at PO7/8. The jackknifing procedure estimates onset latencies from grand averages that are computed from subsamples of participants where one participant is successively excluded from the original sample (Miller, Patterson, & Ulrich, 1998). N2pc onset latencies at each lag were defined as the point in time at which the N2pc difference wave exceeded an absolute voltage threshold value of -0.4 μV. This value was chosen because it was half of the maximum amplitude of the N2pc component. N2pc onset latencies at each lag were examined in a within-subjects analysis of variance (ANOVA) and paired-samples t-tests. F- and t-values were corrected according to the formula described by Ulrich and Miller (2001) and Miller et al. (1998) and are labelled as F_c and $t_{c.}$

Results

Behavioral Performance

The mean percentages of correct T1 and T2 responses, as well as average median RTs to T2, are presented in Table 1. Assessment of behavioral performance was based only on trials in which an oddball was present. This was done to facilitate comparison with the ERP results which can be assessed only when a lateralized stimulus (the oddball) is present.

The grand average of correct T1 responses (standard error in parentheses) was 93.6% (0.9). A one-way within-subjects ANOVA performed on the T1 data yielded no significant effect of Lag ($F < 1$). Estimates of second-target identification were based only on those trials on which the parity of T1 was identified correctly. This procedure is commonly used in AB studies on the grounds that on trials in which the first target fails to be identified, the source of the error is unknown, thus its effect on T2 processing cannot be evaluated. The grand average of correct T2 responses was 99.0% (0.3). A one-way within-subjects ANOVA performed on the T2 data yielded no significant effect of Lag, $F(2, 26) = 1.50$, $p = .243$. The absence of an effect of Lag on either T1 or T2 accuracy was to be expected given that the experiment was designed to optimize response accuracy so as to retain the largest possible number of trials. To this end, we presented no mask after T2 and, to avoid the inherent response ceiling, we used RT instead of accuracy as the dependent measure. The idea that RT and accuracy are both legitimate indices of the AB deficit has been proposed by Ruthruff and Pashler (2001). That idea has been supported by other research showing that much the same pattern of AB results is obtained with T2 search tasks very similar to ours when the dependent measure is accuracy (e.g., Joseph et al., 1997) as when it is RT (e.g., Ghorashi et al., 2007).

Estimates of RT were based only on those trials on which correct responses were made to both targets. Trials with anticipatory RTs (shorter than 200 ms) and very slow responses (RTs longer than 2500 ms) were excluded from analysis (less than 1% of all correct trials). Median RTs to the T2 stimulus were calculated for each observer at each of the three lags. A one-way within-subjects ANOVA performed on the RT data yielded a significant effect of Lag, $F(2, 26) = 100.79$, $p < .001$, $\eta^2 = .886$. A comparison of RT at Lags 0 and 7, $t(13) = 10.87$, $p < .001$, and at Lags 2 and 7, $t(13) = 8.35$, $p < .001$, confirmed that a substantial AB deficit occurred with RT as the dependent measure. RT was slower at Lag 0 than at Lag 2, revealing no evidence of sparing at Lag 0, $t(13) = 9.16$, $p < .001$.

ERP Results

Figure 2 (top panel) shows ERPs obtained for the three Lags (0, 2, 7) at electrodes PO7/8 contralateral and ipsilateral to the side of the T2-colour-oddball. The N2pc components can be seen more clearly in the difference waveforms obtained by subtracting ipsilateral from contralateral ERPs (Figure 2, bottom panel). The presence of N2pc components was confirmed with an ANOVA performed on the mean amplitudes measured at electrodes PO7/8 in the 240-

320 ms post T2-onset time window (Figure 2, top panel). The range of 240-320 ms was selected because the N2pc components were maximal within that time window[1]. A 2 (Laterality: contralateral, ipsilateral) × 3 (Lag: 0, 2, 7) within-subjects ANOVA revealed a significant effect of Laterality, $F(1, 13) = 12.43$, $p = .004$, $\eta^2 = .489$, demonstrating that the N2pc was reliably present. The main effect of Lag was also significant, $F(2, 26) = 36.95$, $p < .001$, $\eta^2 = .740$, revealing that the mean amplitudes of the ERP components differed across Lag. On the face of it, this effect of Lag reflects the finding illustrated in Figure 2 (top panel) that the overall level of the ERP component in the N2pc time range is lower at Lag 2 than at either Lags 0 or 7. This effect is examined in the Appendix. Importantly, however, the Laterality × Lag interaction was not significant, $F = 1.77$, indicating that the differences in mean amplitude between the contra- and ipsilateral ERP components – that is, the mean amplitude of the N2pc components – did not differ across lags.

----- insert Figure 2 about here -----

Of principal interest to the present work was the relative onset latencies of the N2pc components at each Lag. On Ghorashi et al.'s (2007) hypothesis that visual search is postponed during the period of the AB, we expected the latency of the N2pc to the T2 oddball to be longer when the inter-target lag was short than when it was long. A one-way within-subjects ANOVA performed on the N2pc onset latencies yielded a significant effect of Lag, $F_c\,(2, 26) = 4.00$, $p = .031$, $\eta^2 = .235$. Consistent with the postponement hypothesis, paired-samples t-tests confirmed that the N2pc to the T2-oddball emerged sooner at Lag 7 than at either Lags 0 [232 ms vs. 268 ms; $t_c(13) = 2.32$, $p = .037$] or Lag 2 [232 ms vs. 256 ms; $t_c(13) = 3.13$, $p = .008$], revealing an AB in N2pc onset latency. The onset latencies of the N2pc components at Lags 0 and 2 did not differ significantly from one another [268 ms vs. 256 ms; $t_c(13) = .08$, $p = .438$][2].

Discussion

In the present work, we examined Ghorashi et al.’s (2007) claim that visual search for T2 is postponed during the period of the AB. To this end, we used the N2pc as an index of the time at which attention is deployed to the location of T2 in a search array. On the twin premises that (a) the deployment of attention is postponed during the period of the AB, and (b) that the N2pc indexes the time at which attention is deployed to the target, we expected the latency of the N2pc to be longer when the inter-target lag was short than when it was long. The results confirmed that expectation.

Qualitatively, this result is consistent with Ghorashi et al.’s (2007) proposal that visual search is postponed during the period of the AB (i.e., until processing of T1 has been completed). Quantitatively, however, the proposition that the N2pc provides a realistic estimate of that postponement is more problematic. This is because the estimate based on the RT measure (about 300 ms) is considerably longer than the corresponding estimate based on the N2pc measure (about 30 ms). Substantial discrepancies between RT and N2pc-latency differences have been found in several studies (e.g., Corriveau et al., 2012; Lorenzo-Lopez, Amenedo, & Cadaveira, 2008; Wiegand, Finke, Müller, & Töllner, 2013). Other studies, however, have found a close correspondence between the two measures (e.g., Fortier-Gauthier, Dell'Acqua, & Jolicœur, 2013; Luck et al., 2006; Töllner, Zehetleitner, Gramann, & Müller, 2011). The reasons for the different outcomes are unclear and remain to be investigated.

Before relinquishing the discussion of the difference between RT and N2pc latencies, we need to consider the option that such a difference might have arisen from the different ways in which the two values were calculated. The onset latency of the N2pc reflects the *shortest* latency at which the N2pc was elicited across trials at any given lag. In contrast, the mean RT reflects the *average* latency in processing the search array across trials at any given lag. As an extreme example of how the mean RT measure is obtained, consider a bimodal distribution with 600-ms latency on half of the trials and 300-ms latency on the other half. By combining these two distributions, the average latency in RT would be 450 ms. In the case of the N2pc, the distribution of latencies would have a temporal smearing effect on the average amplitude (which would be correspondingly reduced as the variability increased) but would have little or no effect on the average onset latency because it would reflect the shortest latencies, regardless of distribution. This sensitivity to different aspects of the distribution of latencies across trials could, potentially, explain the RT/N2pc differences seen in the present work[3].

----- insert Figure 3 about here -----

The results illustrated in Figures 2 (lower panel) and 3 allow for an unbiased comparison between the RT and N2pc measures (i.e., to compare *onsets* in both cases). To produce Figure 3, we calculated the latency of RTs in a way that was homologous to that used for the N2pc. We generated a frequency distribution of RTs (10-ms bins) for each observer, separately for each lag. The resulting three distributions, averaged over observers, are illustrated in Figure 3 where the abscissa represents time from T2 onset and the ordinate represents the percentage of total trials, separately for each lag. Upon inspection, it is clear that the functions for Lags 0 and 7 differ from one another by considerably more than 30 ms, at any arbitrary value of the ordinate. Thus, the magnitude of the postponement in RT is still greater than the corresponding postponement in N2pc even when the RT and N2pc latencies are computed in similar ways.

One Source of Delay or Many?

Clearly, the estimates based on N2pc and RT cannot always be regarded as measures of the same thing. Rather, the substantial difference in the N2pc and RT measures obtained in the present study may reflect AB-related delays at different stages of processing: deployment of attention to the target in the search display (indexed by the N2pc), and processes that occur after the target has been located, such as extraction of task-relevant information and response planning (included in the RT).

These findings have direct implications for theories of the AB. In most current accounts, the AB deficit is attributed to limitations in the transferring of T2 information into visual short-term memory (VSTM). Some theories (e.g., Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shih, 2008; Wyble, Bowman, & Nieuwenstein, 2009) postulate an explicit bottleneck at the input to VSTM. Other theories (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers, van der Stigchel, & Hulleman, 2007), ascribe the AB to a failure of attentional control.

A common characteristic of all these theories is that the AB arises from events that occur at a single step in the chain of information processing. In contrast to this single-factor view, the present results suggest that the AB arises from bottlenecks and delays at more than one level within the system. This goes against the idea that processing of T2 cannot begin until all attributes of T1 have been processed. Rather, processing of some T2 attributes that require attention could begin when the processing of the corresponding attributes of T1 have been completed. This idea entails a concurrent/successive sequence of processing wherein higher-level processing of some stimulus attributes is initiated even while lower-level processing of other attributes is still under way. Such a system would be compatible with Awh et al.'s (2004) multi-channel account of the AB deficit.

An important consideration regarding the factors that influenced the latency of the N2pc in the present experiment is that a task switch occurred between T1 and T2. It has been hypothesized that "the locus of task-switching interference is located at an early, perceptual level, whereas AB deficits take place at a late, central level" (Vachon, Tremblay, & Jones, 2007, p. 345). On this hypothesis, task switching and the AB are regarded as independent events, with the latency of the N2pc being governed by a task switch, and the accuracy (or the latency) of T2 identification being governed by other factors that produce the AB deficit (Vachon & Jolicœur, 2011; Vachon et al., 2007). On this view, the N2pc would not have been delayed in the absence of a task switch[4]. This proposal, however, cannot be verified on the basis of extant empirical evidence because all the studies in which the N2pc was investigated throughout the period of the AB employed paradigms that involved task switching (Akyürek et al., 2010; Brisson & Jolicœur, 2007; Corriveau et al., 2012; Dell'Acqua et al., 2006; Jolicœur et al., 2006a, b; Lien et al., 2011; Pomerleau et al., 2014; Robitaille et al., 2007; Verleger et al., 2012). At any rate, Vachon et al.'s hypothesis of independence needs to be viewed in the context of input-control theories such as *Boost and Bounce* (Olivers et al., 2007) and *Temporary Loss of Control* (Di Lollo et al., 2005) in which task switching and the AB are not regarded as independent. According to these theories, the critical factor in the AB is a task switch between T1 and the ensuing distractor. Thus, a delay of the N2pc during the period of the AB should be observed even in the absence of a task switch between T1 and T2.

Is Attention Involved in Pop-Out Search?

The type of search task used in the present work is known as "oddball search" because on any given trial the search array contained a target that differed in only one dimension (colour, in this case) from the remaining items. There has been disagreement as to whether the detection of oddball targets requires attention or whether such targets are processed preattentively because they "pop out".

The preattentive option emerged from the finding that RTs to pop-out targets are invariant with the number of distractors in the search display (e.g., Egeth, Jonides, & Wall, 1972; Treisman & Gormican, 1988). The alternative option, that pop-out search involves attention, emerged from two related findings. First, that responses to pop-out targets can be primed, thus implicating attention (Maljkovic & Nakayama, 1994, 1996). Second, that the processing of pop-out targets is impaired during the period of the AB, again pointing to the involvement of attention (Joseph et al., 1997). Our findings that both the latency of the N2pc and the RT to T2 were affected by the AB are clearly in line with the option that pop-out search involves attention.

Concluding Comments

In summary, the present work is characterized by three main themes. First, by adducing electrophysiological evidence, we substantiated Ghorashi et al.’s (2007) claim that visual search is postponed during the period of the AB. Second, the discrepancy between the behavioural and the electrophysiological estimates of the AB-related delay (about 300 ms and 30 ms, respectively), pointed to multiple sources of delay (or multiple bottlenecks) along the chain of processing events. Finally, the present finding that the latency of the N2pc is increased during the period of the AB is clearly consistent with the idea that attention is involved in the processing of pop-out stimuli.

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Footnotes

[1] Following a suggestion by an anonymous reviewer, we extended the analysis window to 600 ms post-stimulus to explore for evidence of a sustained posterior contralateral negativity (SPCN). The extended analysis revealed no evidence of an SPCN component. This is to be expected, as previous studies have found that unlike the N2pc, the SPCN is elicited only in tasks in which response selection requires the in-depth processing and identification of target stimuli. No SPCN is triggered in tasks that simply require the detection of pop-out targets (Mazza, Turatto, Umiltà, & Eimer, 2007).

[2] An additional analysis comparing the size of the N2pc at electrode sites PO7/PO8 and P7/P8 showed that the N2pc was reliably larger at electrodes PO7/PO8 [$F(1, 13) = 7.98$, $p = .014$, $\eta^2 = .380$]. However, a replication of the N2pc amplitude and onset latency analyses at electrode sites P7/P8 mirrored the results found at sites PO7/PO8. The ANOVA on mean amplitudes in the 240-320 ms post-stimulus time window revealed main effects of Laterality, $F(1, 13) = 8.87$, $p = .011$, $\eta^2 = .406$, and Lag, $F(2, 26) = 54.34$, $p < .001$, $\eta^2 = .807$. The Laterality × Lag interaction was not significant, $F = 1.44$. The ANOVA on N2pc onset latencies at an absolute voltage threshold value of -0.4 µV uncovered a main effect of Lag, $F_c\ (2, 26) = 14.15$, $p < .001$, $\eta^2 = .521$. N2pc components to the T2-oddball emerged statistically at the same time at Lag 0 and Lag 2 [275 ms vs. 282 ms; $t_c\ (13) = .09$, $p = .392$], but emerged sooner at Lag 7 relative to Lag 0 [243 ms vs. 275 ms; $t_c\ (13) = 3.65$, $p = .003$] or Lag 2 [243 ms vs. 282 ms; $t_c\ (13) = 5.53$, $p < .001$].

[3] We thank Eric Ruthruff for pointing out this possibility.

[4] We thank an anonymous reviewer for raising this possibility.

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Appendix

Here we provide an account of the significant effect of Lag revealed in the analysis of the mean amplitudes of the ERP components.

----- insert Figure 4 about here -----

Figure 4shows the grand-averaged ERPs measured at electrodes PO7/8, time-locked to the onset of the T1 stimulus, separately for Lags 0, 2, and 7. The figure illustrates how the overall level of ERP components elicited by T2 can be affected by temporal overlap with ERP components elicited by T1. The important point to bear in mind is that the temporal separation between T1 and T2 differs as a function of lag. Therefore, the overlap between the ERP components elicited by T1 and T2 will also differ as a function of lag. How these temporal contingencies affect the overall level of the T2-elicited ERPs can be best seen in the level of the T2-elicited N1 as a function of its temporal overlap with the T1-elicited P3.

At Lag 0 the T2-elicited N1 occurs before the T1-elicited P3, hence its level is virtually unaffected. By the same token, at Lag 7 the N1 occurs after the P3, and its level is similarly unaffected. At Lag 2, however, the timing of the T2-elicited N1 coincides with that of the T1-elicited P3, thus causing the overall level of the ERP in the N1 time-range to become more positive. The same considerations apply to the overall level of the ERP components involved in the computation of the N2pc (Figure 2, top panel). The effects of overlapping components on overall level resulted in the significant effect of Lag revealed in the analysis of the mean amplitudes of the ERP components in the latency range of the N2pc. It should be emphasized that, because it is displayed foveally, T1 does not elicit lateralized ERP components. Given the lateralized nature of the N2pc, this rules out the possibility that any T1-elicited component may have affected the T2-elicited N2pc.

Table 1

Mean Median Reaction Times (RTs) and Percentages of Correct Responses (standard error in parentheses)

	Target Absent			Target Present		
Measure	Lag 0	Lag 2	Lag 7	Lag 0	Lag 2	Lag 7
% correct T1	93.4 (1.3)	93.4 (1.2)	93.4 (0.8)	94.7 (1.5)	93.8 (1.1)	93.5 (1.0)
% correct T2|T1	96.8 (1.3)	98.1 (0.8)	99.6 (0.2)	98.9 (0.3)	99.3 (0.3)	99.4 (0.2)
Median RT (ms)	958 (61)	812 (54)	708 (60)	981 (56)	761 (47)	668 (47)

Figure Captions

Figure 1. Schematic diagram of the display sequence. The first target (T1) was a digit, the parity of which had to be reported. The second target (T2) was a search array of six coloured rings. The rings were either all of the same color (red or green) or contained one colour-oddball (one red ring amongst five green rings, or one green ring amongst five red rings). There were three inter-target lags: At Lag 0, the onset of T2 was simultaneous with that of T1. At Lags 2 and 7, the onset of T1 preceded that of T2 by 200 ms and 700 ms, respectively.

Figure 2. Grand-averaged ERPs measured at posterior electrodes PO7/8 contralateral and ipsilateral to the location of the T2-oddball at Lags 0, 2, and 7. The bottom panel shows difference waveforms obtained by subtracting ipsilateral from contralateral ERPs in response to the T2-oddball at each Lag.

Figure 3. Grand-averaged frequency distribution of T2 RTs time-locked to the onset of the T2 search array, separately for Lags 0, 2, and 7. The abscissa represents time from T2 onset and the ordinate represents the percentage of total trials.

Figure 4. Grand-averaged ERPs measured at posterior electrodes PO7/8 time-locked to the onset of the T1 stimulus, separately for Lags 0, 2, and 7.

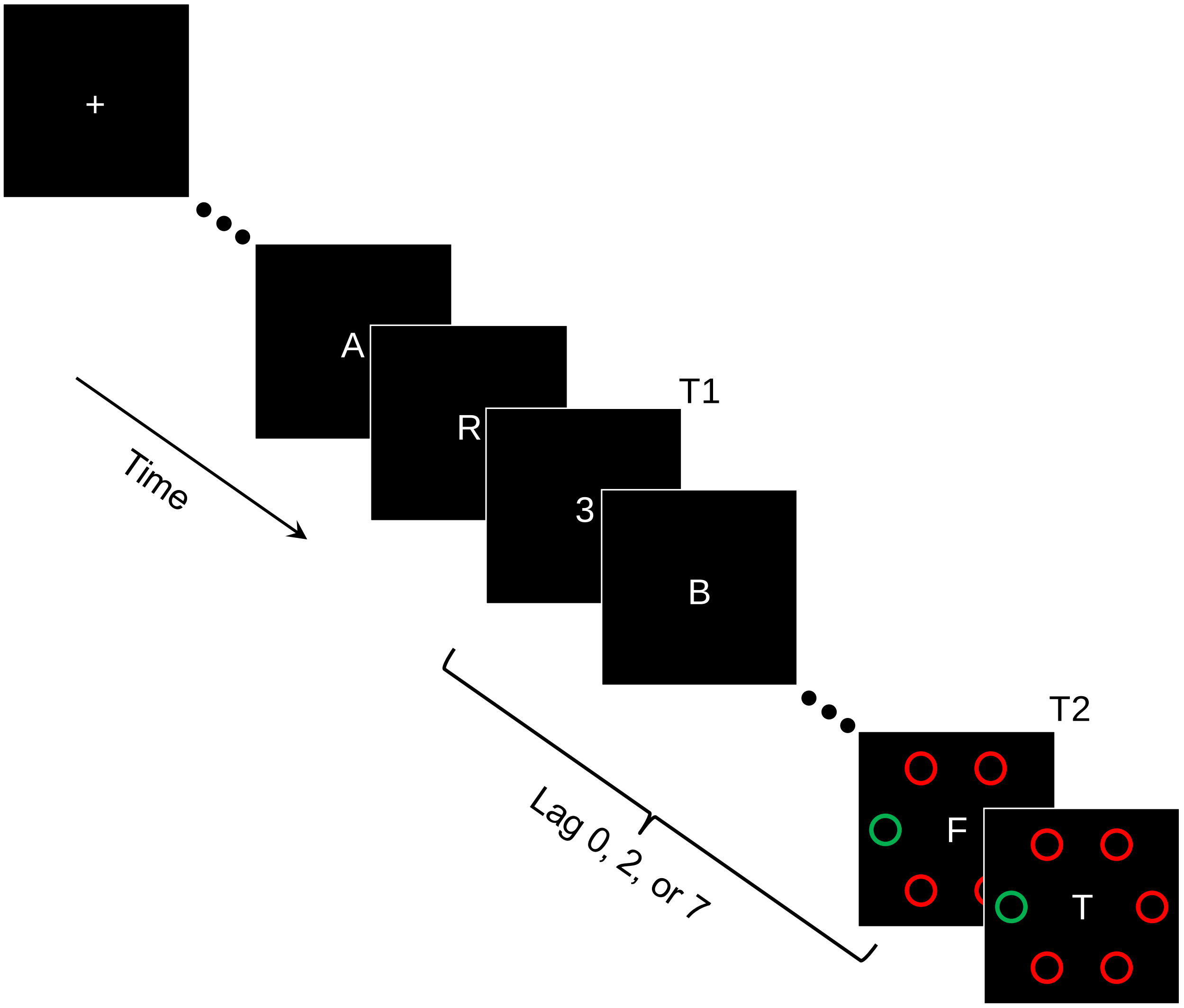

Figure 1

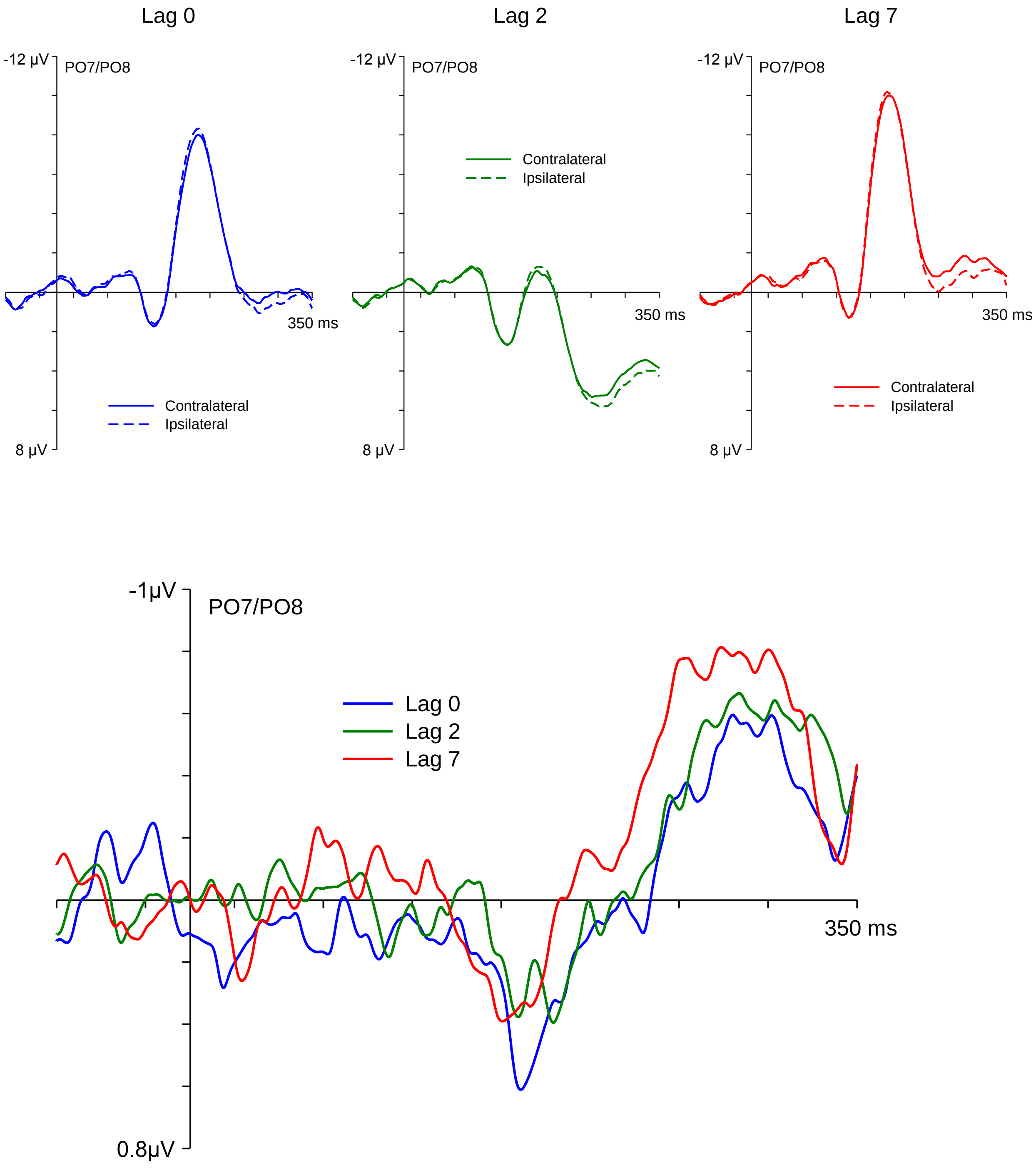
Lag 0
-12 µV
PO7/PO8
350 ms
Contralateral
Ipsilateral
8 µV
Lag 2
-12 µV
PO7/PO8
Contralateral
Ipsilateral
350 ms
8 µV
Lag 7
-12 µV
PO7/PO8
350 ms
Contralateral
Ipsilateral
8 µV
-1µV
PO7/PO8
Lag 0
Lag 2
Lag 7
350 ms
0.8µV

Figure 2

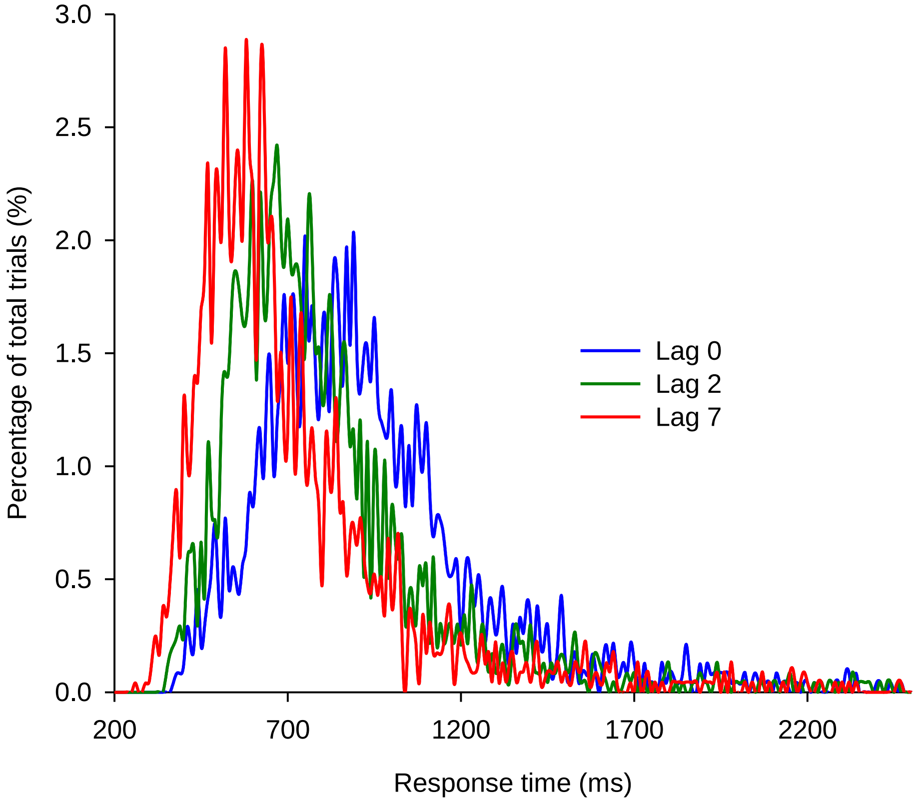
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Percentage of total trials (%)
200
700
1200
1700
2200
Response time (ms)
Lag 0
Lag 2
Lag 7

Figure 3

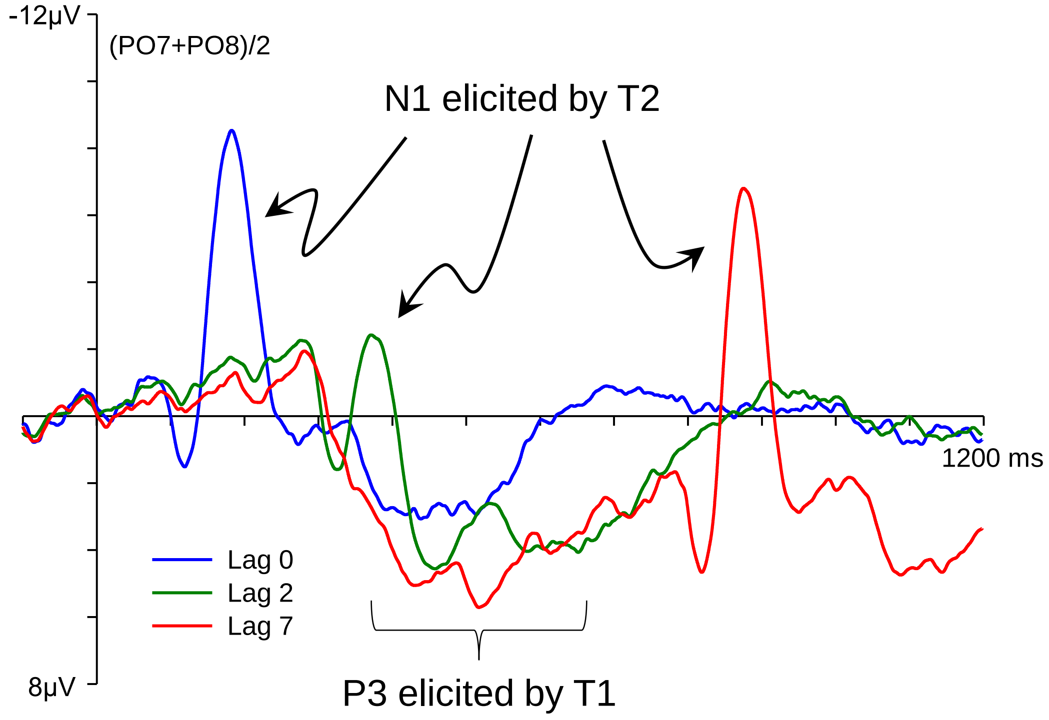
-12μV
(PO7+PO8)/2
N1 elicited by T2
1200 ms
Lag 0
Lag 2
Lag 7
8μV
P3 elicited by T1

Figure 4