Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology

Pierre Jolicœur

Université de Montréal, Montréal, Canada

Paola Sessa and Roberto Dell'Acqua

University of Padova, Padova, Italy

Nicolas Robitaille

University of Montreal, Montreal, Canada

We studied attentional control mechanisms using electrophysiological methods, focusing on the N2pc event-related potential (ERP), to track the moment-by-moment deployment of visual spatial attention. Two digits (T_1 and T_2, both red or both green, and masked, were embedded in a rapid serial visual presentation of letter distractors with an SOA of 200 ms or 800 ms. T_1 was at fixation, whereas T_2 was $3°$ to the left or right of fixation and presented with a concurrent equiluminant distractor digit in a different colour. T_1 and T_2 were reported in one block of trials, and only T_2 in another block (order counterbalanced). Accuracy for T_2 was lower at short SOA than at long SOA when both T1 and T2 were reported, suggesting an attentional blink (AB) effect. It was difficult to ignore T_1 because T_1 had the same colour as T_2, producing a large deficit in T_2 accuracy at short SOA in the control condition. The amplitude of the N2pc ERP component was attenuated in the short-SOA condition relative to the long-SOA condition, both in the experimental and the control conditions, suggesting that T_1 involuntarily captured visual spatial attention and that while attention was deployed on T_1, the processing of T_2 was significantly impaired.

We used human electrophysiology to study attentional control mechanisms for the deployment of visual spatial attention, in the context of the attentional blink paradigm. Our goal was to study capacity limitations in the mechanisms involved in the control of visual spatial attention. Attentional selection is thought to be necessary because capacity limitations in later stages of processing make it impossible to process all of the

Correspondance should be addressed to Dr. Pierre Jolicœur, Département de Psychologie, Université de Montréal, C.P. 6128 Succursale Centre-ville, Montréal Québec, Canada, H3C 3J7. Email: pierre.jolicoeur@umontreal.ca

information available in the visual array (Pinker, 1984; Sperling, 1960; Treisman & Gelade, 1980). Only a subset of the information can be processed fully, and thus some information must be selected for further processing and some information must be left out. Attributes of the stimuli, such as spatial location, colour, luminance, and size, can be used as the basis for selection (Posner, 1980; Sperling, 1960; von Wright, 1972).

Interestingly, there is an electrophysiological consequence associated with the selection of information for further processing. This electrophysiological response is elicited using the event-related potential (ERP) technique, and has been studied extensively by several researchers, and most particularly by Luck and his colleagues (e.g., Eimer, 1996; Girelli & Luck, 1997; Hopf, Boelmans, Schoenfeld, Heinze, & Luck, 2002; Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994; Woodman & Luck, 2003). Luck and his colleagues refer to this ERP component as the N2pc (N2 because the latency of the component is about the same as the N2, with an onset about 200 ms post stimulus, and "pc" for posterior contralateral, indicating the electrode sites where the response is maximal).

When attention is allocated to a target in the left or right visual field, the ERP response at posterior electrode sites is more negative for electrodes contralateral to the side of the target than for electrodes on the ipsilateral side. The N2pc is the difference in measured voltage at posterior lateralised electrode sites. The N2pc can be used to track the moment-to-moment allocation of attention (Woodman & Luck, 2003), and we used this index to study the relationship between the mechanisms that mediate visual spatial attention and those that mediate central attentional operations. Furthermore, we did so under conditions that could lead to attentional capture based on top-down attentional control settings (Folk, Leber, & Egeth, 2002; Folk, Remington, & Johnston, 1992).

Folk and his colleagues have produced an impressive body of work that supports the idea that the degree to which a target involuntarily captures attention depends on top-down attentional control settings controlled by the observer's goals. For example, an observer expecting to detect a uniquely colored target (e.g., red) presented in a rapid sequence of stimuli in other colours, at fixation, will be significantly distracted (attention capture) by a distractor presented in the periphery if that distractor matches the colour of the target (e.g., red) but not if the distractor is in another colour (e.g., green; Folk et al., 2002). Such results demonstrate that attention control settings can exert a top-down influence on the degree to which bottom-up signals can capture spatial attention.

In the present work we sought to provide a more direct test of the dependence of the control of spatial attention on central attentional mechanisms and on top-down control settings. We used the N2pc as an electrophysiological marker of the moment-by-moment deployment of visual

spatial attention to monitor when and where observers were attending, while they performed concurrent central processing known to cause an attentional blink (Jolicœur, 1999; Vogel, Luck, & Shapiro, 1998).

Figure 1 shows how we adapted the attentional blink paradigm for use with the N2pc ERP technique. Subjects initiated each trial by pressing the space bar, which triggered the presentation of a stream of characters shown at fixation using rapid serial visual presentation (RSVP). The RSVP stream consisted of white upper-case letters on a black background, each shown for 100 ms. Each subject searched either for red or for green digits during the presentation sequence (half searched for each colour). T_1 and T_2 were always presented in the designated colour. T_1 was presented at fixation (replacing one of the distractor letters), and T_2 was presented 3° to the left or right of fixation. As can be seen in Figure 1, T_2 was accompanied by another digit, presented in the other visual field, and in a different colour (i.e., green if T_1 was red, or red if T_1 was green). T_2 and the concurrent distractor digit were followed by identical bilateral masks (i.e., the letter "W"), to ensure that we had conditions required for the attentional blink (Giesbrecht & Di Lollo, 1998).
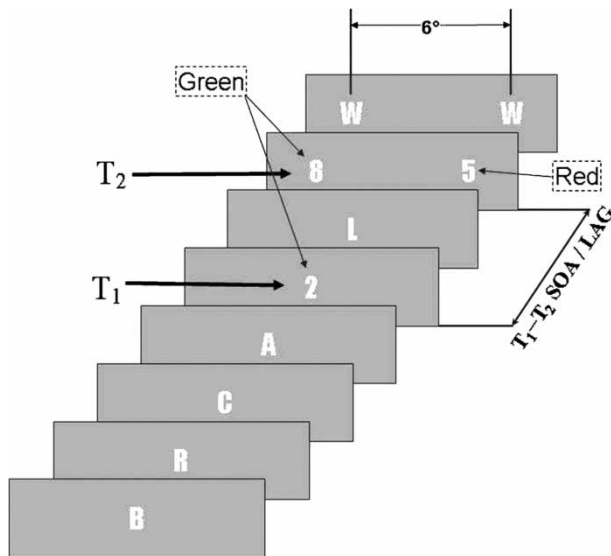

Figure 1. Stimulation sequence in the experiment. T_1 and T_2 were presented in either red or green, among white distractor letters. The stimuli were presented for 100 ms each, with no blank intertial interval. T_1 was always followed by one letter (lag-2) or seven letters (lag-8). T_2 was presented 3° to the left or right of fixation with a concurrently with a distractor presented symmetrically on the other side of fixation, in a different colour. In this example, T_1 and T_2 were green, and T_2 was in the left visual field. The visual field of presentation of T_2 varied from trial to trial, and the colour of T_1 and T_2 (red vs. green) was counterbalanced across subjects.

We manipulated the SOA between T_1 and T_2 (either 200 or 800 ms) by adding more intervening distractor letters at the center of the display when the lag was longer. Furthermore, each subject was tested in two blocks of trials. In one block they attempted to report the identity of both of the two digits (T_1 and T_2) that had been shown. In the other block (counterbalanced for order across subjects), they only reported T_2.

The experimental design was based on the following logic. In the report-T_1 condition, encoding T_1 should occupy central mechanisms and this should produce the conditions required to observe an attentional blink (Jiang & Chun, 2001; Jolicœur, 1999; Vogel et al., 1998). When T_2 is presented 200 ms after T_1 (lag-2), some aspect of the processing of T_2 suffers because a central mechanism or capacity is occupied by the ongoing processing of T_1 (Jolicœur, 1999). When T_2 is presented 800 ms after T_1 (lag-8), and thus relatively long after T_1, the encoding of T_1 should be completed and any interference on T_2 would likely be attributable to the load of maintaining a memory representation of T_1 until the end of the trial (Jolicœur & Dell'Acqua, 1998). This memory maintenance load should be smaller than the encoding cost, and so performance in $Task_2$ (the task performed on T_2) should recover to near-baseline levels at lag-8.

In many AB experiments the control condition consists of trial blocks in which T_1 is presented but can be ignored (Jolicœur, Sessa, Dell'Acqua, & Robitaille, in press; Raymond, Shapiro, & Arnell, 1992). In this type of design the experimental condition (report T_1 and T_2) and the control condition (report T_2 only) are equated in terms of physical stimulation and stimulus presentation because the same stimulus sequences are used in both conditions. Normally, the control condition allows subjects to ignore T_1 effectively, leading to a very low processing load before the onset of T_2. When T_2 is presented it can be processed without competition from processing of T_1, leading to very good performance and, importantly, performance that is unaffected, or only weakly affected, by the lag between T_1 and T_2. Indeed, this is exactly the pattern of results that was obtained by Jolicœur et al. (in press) using presentation parameters that were nearly identical to those used in the present experiment, but that differed in that T_1 was presented in white rather than in the same colour as T_2.

Another result reported by Jolicœur et al. (in press) was critical: The N2pc ERP component was modulated strongly by the experimental conditions defining the AB paradigm. Most importantly, the N2pc was completely abolished in the attend-T_1, lag-2, condition, and was partly suppressed in the attend-T_1, lag-8, condition, relative to the ignore-T_1 conditions. These results suggested that the ability to deploy visual spatial attention to the location of T_2 suffered when attention was also allocated to T_1. Recall that T_1 was presented in white in this experiment, whereas T_2 was presented in red or green.

In the present experiment we wished to discover the impact of presenting T_1 in the same colour as T_2. We anticipated two possible consequences of this manipulation. Consider first what might happen in the experimental condition, when both T_1 and T_2 are to be reported, and contrast the present situation with the one instantiated in the Jolicœur et al. (in press) experiment. In this former experiment we hypothesised that subjects had to maintain two different selection strategies for T_1 and T_2. For T_1, which was not coloured differently than the distractors in the central RSVP stream, selection was likely based on character identity or category. In contrast, for T_2, colour had to be used as a selection cue because T_2 was presented concurrently with another digit. Thus, character identity or category could not be used to determine which of these two digits was to be encoded and reported, and selection had to be based on the colour of T_2.

In the present experiment, by presenting T_1 in the same colour as T_2, subjects could adopt a single selection strategy for both T_1 and T_2. That is, subjects could always select targets based on colour, avoiding the need to change selection strategy from T_1 to T_2. The difference across the present experiment and that of Jolicœur et al. (in press) allows us to test whether the suppression of the N2pc component observed by them was due to the change in selection strategy or to the processing of T_1, per se. Such a change in selection strategy could be conceived as a type of task switch, which has been argued to influence performance in the AB paradigm (e.g., Potter, Chun, Banks, & Muckenhoupt, 1998; Visser, Bischof, & Di Lollo, 1999). If it was the change in selection strategy (and/or a task switch) that made it difficult for subjects to deploy attention to T_2, then allowing subjects to adopt a single selection strategy should facilitate attentional deployment. If so, we should observe no attenuation of the N2pc across lag in the experimental condition of the present experiment. If it was the processing of T_1 that occupied mechanisms and/or resources also used by spatial attentional control systems, then the N2pc should also be suppressed in the present experiment at lag-2 relative to lag-8.

Now consider the control condition. Here subjects wished to process only T_2 while ignoring T_1. Ignoring T_1 was relatively easy in the experiment of Jolicœur et al. (in press) because T_1 was presented at fixation, in white among white distractors, whereas T_2 was uniquely coloured and presented off fixation. In the present experiment, however, T_1 had the same colour as T_2. We anticipated this would make it more difficult to ignore T_1 because of the match between the colour of T_1 and the cue used to select T_2, namely colour. Indeed, there is good reason to believe that this colour match would cause attention to be captured involuntarily by T_1 (Dell'Acqua, Jolicœur, Sessa, & Turatto, 2006 this issue; Folk et al., 2002). If visual spatial attention is captured by T_1, in the control condition, attention may not have time to shift to the location of T_2 and engage on T_2 in time to avoid the deleterious

effects of the mask that follows T_2. However, this effect should only occur when the SOA between T_1 and T_2 is short. At the long SOA (800 ms), attention would have time to disengage from T_1 allowing it to shift and engage on T_2 rapidly.

Based on the foregoing considerations, we anticipated that the involuntary capture of visual spatial attention by T_1, in the control condition, would cause both a decrease in report accuracy for T_2 as well as an attenuation of the amplitude of the N2pc (based on the results of Jolicœur et al., in press), at the short SOA relative to the long SOA.

In summary, the present experiment allowed us to measure the impact of the colour match between T_1 and T_2 both on the usual behavioural measure of the AB, namely the accuracy of report of the identity of T_2, as well as on the ability to shift visual spatial attention to T_2 in the control and experimental conditions of an AB paradigm. This latter measure was derived from the electrophysiological recordings and the event-related potential (ERP) technique that we used to isolate the N2pc component (Jolicœur, et al., in press; Luck & Hillyard, 1994; Woodman & Luck, 2003).

METHOD

Subjects

The subjects were 16 neurologically normal undergraduate students at the University of Padova who participated voluntarily. All reported having normal or corrected visual acuity and normal colour vision.

Stimuli and procedure

The stimuli were white uppercase letters and coloured digits (2–9) on a black background, presented using a cathode ray tube monitor controlled by a microcomputer. The luminance of the characters (white, red, or green) was adjusted using a chromameter so they were all approximately equiluminant. The characters were presented using rapid serial visual presentation (RSVP). Each stimulus was exposed for 100 ms with no blank interstimulus interval. As illustrated in Figure 1, the RSVP stream started at fixation and included T_1, and it later became bilateral with the appearance of T_2.

There were 6–9 stimuli (this number selected randomly at run time) in the central RSVP stream prior to T_1, and 1–7 (also randomised at run time) in the central stream following T_1, depending on the lag (one after T_1 at lag-2, and seven after T_1 at lag-8). Thus, there was always at least one letter following T_1, in order to backward-mask T_1 and maximise the AB (Raymond et al., 1992; Seiffert & Di Lollo, 1997).

The frame containing T_2 was presented, 200 ms (lag-2) or 800 ms (lag-8) after T_1. The T_2 frame had a red digit the centre of which was either 3° to the left or right of fixation, and a green digit that was equally far from fixation in the opposite visual field. One of these digits was T_2 (defined as the digit in the appropriate colour), and T_2 occurred to the left or right of fixation at random with equal probability, from trial to trial. Each of the two digits in the T_2 frame was followed by the letter "W", which acted as a bilateral backward pattern mask.

On every trial, distractor items in the RSVP stream were selected at random, without replacement, from the set of upper-case letters of the alphabet, excluding the letter "W". The letters subtended about 1° of visual angle.

A pair of symbols (e.g., + +) was presented at the centre of the screen at the beginning of each trial. The symbols provided feedback for performance in the previous trial and acted as a fixation point in the current trial. The left symbol indicated accuracy for the previous T_1 response and the right symbol, accuracy for T_2. A + sign indicated a correct response and a − sign indicated an error. Each trial was initiated by pressing the space bar on the computer keyboard, which caused the fixation/feedback symbols to disappear and triggered the onset of the RSVP stream.

The experiment consisted of two back-to-back sessions of 384 trials each (order counterbalanced across subjects). In one session participants were instructed to ignore T_1 and to respond only to T_2; in the other session participants responded to both T_1 and T_2. The target colour was red for half of the subjects and green for the others.

At the end of each trial, participants used the numeric keypad to enter the identity of T_1 and T_2, in the experimental condition, or of just T_2, in the control condition. Subjects were instructed to guess when uncertain. In pilot work, we found that subjects had a strong tendency to look at the numeric keypad very quickly after the presentation of T_2, which introduced unwanted eye movement artifacts in the post-T_2 window we used for the ERP analyses. To minimise the frequency of such artifacts, subjects were instructed and trained to execute their responses without moving their eyes from the central fixation point until they had finished responding to the digits, prior to the beginning of the first test session.

Electrophysiological recording and analysis

Continuous electroencephalographic (EEG) activity was recorded during each session using tin electrodes mounted in an elastic cap with electrodes at Cz, C3, C4, Fz, F3, F4, F7, F8, Fp1, Fp2, O1, O2, Pz, P3, P4, T3, T4, T5, T6, using the International 10/20 nomenclature. In this paper we focus on the three posterior lateralised electrode pairs, (O1, O2), (P3, P4), and (T5,

T6), in the montage where we expected to observe the N2pc component of interest. These sites and the right earlobe were referenced to the left earlobe during recording, and the ERP waveforms were algebraically rereferenced to the average of the left and right earlobes during later analyses. The electrooculogram (EOG) was recorded by a pair of electrodes positioned lateral to the left and to the right eyes to monitor horizontal eye movements and a pair of electrodes positioned above and below the left eye to monitor eye blinks. The EEG and the EOG were amplified with a bandpass filter of 0.01–80 Hz, and sampled at a rate of 250 Hz. The impedance at each electrode site was maintained below 5 $K\Omega$.

Periods of the EEG during which subjects blinked or moved their eyes were identified and these portions were eliminated from the ERP analyses. On average, 9.5% of the trials were rejected because of ocular artifacts. As a check for residual horizontal eye movements, the HEOG was averaged separately for trials in which T_2 was in the left visual field and trials in which T_2 was in the right visual field. The maximum deflection towards the target was about 1 µV, indicating that, on average, subjects moved their eyes less than $1/10°$ in the direction of the target, in the trials that we retained for further analysis.

For each trial, the EEG was segmented from -200 ms to $+500$ ms relative to the onset of T_2. A baseline correction was applied, based on the average amplitude of the signal during the 200 ms prestimulus interval, and the baseline-corrected segments that were not contaminated by ocular artifacts were averaged for each condition, for each subject, separately for trials in which T_2 was on the left of fixation and trials in which T_2 was on the right. For each electrode pair, the waveform observed at the left-sided electrode when T_2 was presented on the right was averaged with the waveform for the right-sided electrode when T_2 was on the left, yielding the average waveform contralateral to T_2. We also computed the average waveform ipsilateral to T_2, for each electrode pair. Finally, we computed the N2pc difference wave by subtracting the ipsilateral waveform from the contralateral waveform. The N2pc was quantified by computing the mean amplitude between 160 and 270 ms. The later contralateral negativity, or SPCN (sustained contralateral posterior negativity), was quantified as the mean amplitude between 300 and 500 ms.

RESULTS

Behavioural results

Consider first the accuracy of report of the identity of T_2, on trials on which T_1 was reported accurately, for each condition (ignore-T_1 vs. report-T_1) and lag (2 vs. 8). The means are shown in Figure 2. The means were submitted to
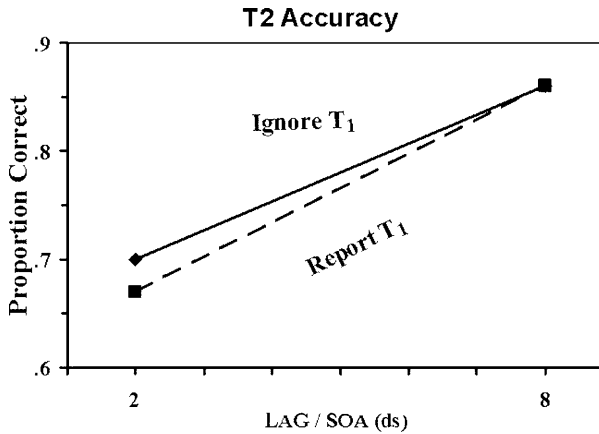
Figure 2. Behavioural results. Proportion correct report of T_2 (contingent on correct report of T_1 in the report-T_1 condition), for each condition (ignore-T_1 vs. report-T_1) and each lag (2 vs. 8).

an ANOVA with condition and lag as within-subjects factors. The proportion of correct reports was .69 at lag-2 and .86 at lag-8, $F(1, 15) = 78.34$, $MSE = 0.006203$, $p < .0001$. There was no overall difference between the accuracy of report for the ignore-T_1 condition (.78) and the report-T_1 condition (.77), $F < 1$.

   As can be seen in Figure 2, the effect of lag was very similar across conditions, and possibly just slightly larger in the report-T_1 condition than in the ignore-T_1 condition, as reflected by the interaction between lag and condition, which only approached significance, $F(1, 15) = 2.98$, $MSE = 0.002358$, $p < .105$.

   In the report-T_1 trials, T_1 accuracy was higher at lag-8 (.957) than at lag-2 (.939), $F(1, 15) = 7.22$, $MSE = 0.000367$, $p < .027$. This result suggests that there may have been a small degree of capacity sharing in the processing of T_1 and T_2—diverting a small proportion of the processing capacity normally allocated to T_1 to T_2 would reduce the efficiency of processing for T_1, causing a small decrement in accuracy (see Tombu & Jolicœur, 2003).

Electrophysiological results

Figure 3 displays the N2pc difference waveforms for the two lags and two Task$_1$ conditions (report-T_1 vs. ignore-T_1), at electrode sites T5/T6, where the N2pc had the maximum amplitude. The results were clear-cut: In the N2pc time window (160–270 ms), the amplitude of the N2pc was higher at lag-8 than at lag-2, regardless of Task$_1$ conditions. Indeed, the waveforms for the ignore-T_1 and the report-T_1 conditions were nicely superimposed within
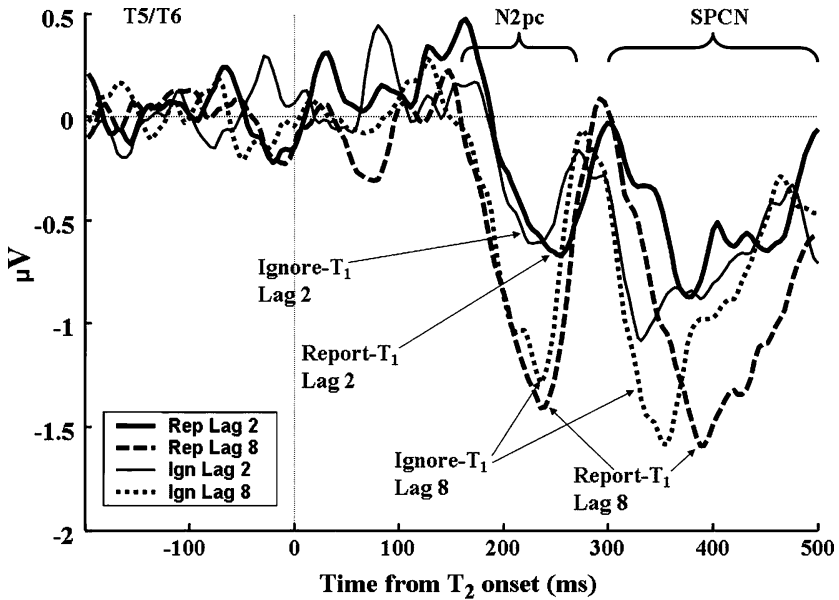
Figure 3. Electrophysiological results. Contralateral minus ipsilateral difference waves for the T5/T6 electrode pair, for each condition (ignore-T_1 vs. report-T_1, at lags-2 vs. 8). The N2pc component is visible in the 160–270 ms time window. Note the second sustained posterior contralateral negativity (SPCN) observed from 300–500 ms. Negative is plotted down.

each lag condition. The mean amplitudes for the N2pc were submitted to an ANOVA that treated $Task_1$ conditions and lag as within-subjects factors. The mean amplitude was higher at lag-8 (-0.80 µV) than at lag-2 (-0.29 µV), $F(1, 15) = 45.25$, $MSE = 0.091104$, $p < .0001$. There were no significant differences, overall, between the ignore-T_1 and the report-T_1 conditions, $F < 1$, and no interaction between $Task_1$ conditions and lag, $F < 1$. The same pattern of ANOVA results was observed at electrode sites O1/O2, and P3/P4, but with smaller absolute amplitudes for the N2pc.

The results in Figure 3 also revealed interesting differences in the lateralised waveforms following the N2pc time window. We investigated these effects by computing the mean amplitude of the contralateral minus ipsilateral waveforms in the 300–500 ms time window. For expository purposes we refer to this response as the SPCN, reflecting the posterior contralateral negativity (after the N2pc). We report here the ANOVA for the amplitudes recorded at the T5/T6 electrode sites (similar patterns of results were observed at O1/O2 and P3/P4, although the effects were weaker at P3/P4). The mean amplitude was -0.75 µV for the lag-2 condition and -0.94 µV for the lag-8 condition, $F(1, 15) = 5.86$, $MSE = 0.311383$, $p < .03$. There was no overall difference across the attend and ignore conditions,

$F < 1$, and the interaction was not significant, $F(1, 15) = 2.82$, $MSE = 0.156920$, $p > .11$.

The N2pc results shown in Figure 3 also suggested that the onset of the N2pc may have been delayed at lag-2 relative to the onset at lag-8, both for the ignore-T_1 and the report-T_1 conditions. We examined this possibility using a jackknife procedure in which we estimated the time at which the N2pc component reached an amplitude of 50% of the peak amplitude of the component (see Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). This analysis was carried out on the waveforms measured at the T5/T6 electrode pair for the four main experimental conditions shown in Figure 3. None of the latency differences were significant ($p > .27$ in all cases).

A similar jackknife procedure was used to analyse the onset of the SPCN component. The mean estimated half-amplitude latency of the SPCN, for the T5/T6 electrodes, was 304 ms for the ignore-T_1 condition and 341 ms for the report-T_1 condition, $F(1, 15) = 11.02$, $p < .005$. Neither the difference across lags nor the interaction between lag and $Task_1$ conditions approached significance ($F < 1$ in both cases).

DISCUSSION

The experiment revealed very interesting patterns of behavioural and electrophysiological results that bear on the issue of the relationship between spatial and central attention, on the one hand, and on the influence of top-down attentional settings on the deployment of visual spatial attention, on the other.

Consider first the results from the experimental condition, across lags. The accuracy of the report of the identity of T_2 decreased as lag was reduced, as expected from previous research on the AB phenomenon. More importantly, the N2pc ERP component, which is believed to reflect the locus of visual spatial attention (e.g., Woodman & Luck, 2003), was sharply attenuated at lag-2 relative to the amplitude at lag-8. These results suggest that attention could not be efficiently redeployed to T_2, following deployment to T_1, despite the fact that T_2 had the same colour as T_1. The results are particularly important in the context of the earlier results of Jolicœur et al. (in press), which used essentially the same paradigm as the present experiment, except that T_1 was white in that experiment, rather than in the same colour as T_2 in the present work. Both experiments yielded sharp attenuations of N2pc as lag was reduced. One hypothesis we entertained in the introduction was that using identical colours for T_1 and T_2 could reduce the selection difficulty of the present tasks by allowing subjects to adopt a single selection rule (e.g., select and process green things). The present results suggest that the change of selection rule required in the experiment of

Jolicœur et al. (in press) was not the critical factor causing the reduction of N2pc amplitude. Had that been so, we should have found no such reduction in the present experiment because a change of selection criteria was not necessary.

Thus, the results suggest that some other aspect of the task was associated with the reduction of N2pc in the earlier experiment, as well as in the present one. One possibility is that the processing of T_1 engaged central processing mechanisms (e.g., short-term consolidation) and that the deployment of visual spatial attention depends on control mechanisms that overlap with those required for the central processing of T_1. In this view, AB is caused by a relatively late bottleneck, and the AB effects on N2pc reflect interactions between central attention and visual spatial attention. Another possibility, however, is that processing T_1 involved some degree of visual attentional capture in both experiments. In the present experiment, it is easy to imagine that the search for a digit in a particular colour (e.g., red) would be associated with attentional capture at the location of T_1. Such capture would be consistent with the results of Folk et al. (2002), and with the results in the control condition, in which attention appears to have been captured by T_1 despite instructions to ignore it.

The role of attentional capture is less clear for the Jolicœur et al. (in press) experiment than for the present one. In Jolicœur et al., T_1 was presented in the same colour as the distractor letters in the central RSVP stream. It is not clear that a difference in category membership (digit vs. letter) would be associated with involuntary attentional capture. Indeed, results from the control condition in the Jolicœur et al. experiment, in which the report accuracy for T_2 was only minimally affected by lag, suggest that there was no involuntary capture by T_1 when subjects tried to ignore T_1. In that case, subjects were successful in escaping from spatial capture and presumably from processing costs associated with processing of T_1 beyond an initial spatial selection.

In the present experiment, the effect of lag in the experimental condition was very similar in magnitude to that observed in the corresponding condition in the experiment of Jolicœur et al. (in press). This suggests that the capture of visual spatial attention, per se, may not be the cause of the processing deficit found in Task$_2$. Rather, it is possible that engaging attention on T_1, in a context in which T_1 and T_2 are both digits, is sufficient to trigger the further processing of T_1 and cause conflict at the level of short-term consolidation (Jolicœur & Dell'Acqua, 1998). If so, it is possible that the AB in both experiments was caused by capacity limitations at a relatively late stage of processing, in all cases in which there were substantial SOA effects (i.e., the experimental condition in Jolicœur et al., and both conditions in the present experiment). In this view, attentional capture, under present conditions (i.e., encoding digits presented among letter

distractors) is associated with further processing of the digit, and that further processing causes both a deficit in the later treatment of T_2, as well as in the deployment of spatial attention to T_2.

The results from the control condition are also particularly interesting. In this case, it seems very clear that subjects found it difficult to ignore T_1 and thus that T_1 involuntarily captured attention. The sharp reduction of N2pc at the short lag relative to the long lag converged with the behavioural results by suggesting that the deployment of attention to T_2 was impaired relative to what we observed at the long lag. The analysis of the onset latency of the N2pc also provided little evidence suggesting that the deployment of attention may have been delayed at lag-2 relative to lag-8, although the waveforms were suggestive.

The results provide clear-cut evidence for substantial modulations of the amplitude of the N2pc component. There are likely many stages of processing between the onset of T_2, and the deployment of visual spatial attention to T_2. In the present work (and in the experiment of Jolicœur et al., in press), T_2 was selected on the basis of colour. One may wonder, therefore, whether the processing of colour information, per se, may have been impaired by the AB, or by attentional capture, rather than the deployment of attention. We tested this possibility in a control experiment in which Task$_2$ was to indicate not the identity of the T_2 digit, but rather simply on which side T_2 had been presented. If information about the colour of T_2 was available to early processing mechanisms, and if the AB, and/or attentional capture, did not render this information inaccessible, then performance should be higher and less affected by the T_1–T_2 lag than for the accuracy of report of T_2 identity.

When Task$_2$ was to report the side (left vs. right) on which T_2 was presented, responses were 96.5% correct at lag-2 (97% for the ignore-T_1 condition vs. 96% for the report-T_1 condition) and 93% correct at lag-8 (93% for both conditions). Although this effect of lag was significant, indicating that some aspect of the side-of-colour task was impaired by the AB (possibly encoding into memory the outcome of the decision as to the location of T_2), the magnitude of the effect (3.5%) was much smaller than for the T_2 identity task (17%). The more than fourfold reduction in the size of the lag effect in the control experiment suggests that it is unlikely that the lag effects observed in the T_2 identity task were caused by a problem in the early perception of the colours of T_2 and the T_2 distractor. The control experiment thus supports our interpretation of the attenuation of the N2pc at lag-2 as a reflection of interference with the control of visual spatial attention.

Although the perception of colour, per se, did not appear to be sufficiently impaired by the AB to produce the observed decrease in the amplitude of the N2pc, perhaps the AB disrupts the maintenance of top-down attentional control settings required to initiate an attentional shift

toward the target location, based on colour. This is a more specific possibility for the locus at which the AB might interfere with the control of visual spatial attention. The fact that subjects were able to remember what task to perform in the colour control experiment, however, suggests that a disruption with the maintenance of information already in the system, per se, is not as likely as a disruption in the ability to control behaviour on the basis of information in the system.

The AB has been claimed to be caused at a relatively late stage of postperceptual processing, such as the short-term consolidation of T_2 into short-term memory (e.g., Chun & Potter, 1995; Crebolder, Jolicœur, & McIlwaine, 2002; Jolicœur, 1999; Jolicœur & Dell'Acqua, 2000), and even after processing of T_2 achieves access to semantics (Vogel et al., 1998). How can we reconcile results suggesting a late locus for the AB bottleneck and the apparently much earlier locus suggested by the reduction of N2pc in the present work (see also Jolicœur, et al., in press)? We note that at least one of the authors, prior to seeing the results from the present experiment and from that of Jolicœur et al. (in press), had predicted that N2pc would not be affected by the AB in these paradigms. This prediction was clearly incorrect, however, and shows that the results were not due to experimenter expectancy effects! Suppose that the N2pc reflects the actual deployment of visual spatial attention, rather than something that takes place afterwards (more down-stream from the attentional shift). In this case, the attenuation of N2pc caused by processing T_1 in the present work (see also, Jolicœur et al., in press) would imply that the AB prevented the deployment of spatial attention for some period of time. Such a result would be consistent with the abolition of lag-1 sparing (Visser et al., 1999) that is usually observed when T_1 and T_2 do not occur at the same spatial location. We chose to present T_2 at lag-2, however, precisely because previous work suggested that the AB function is not affected beyond lag-1 by changes in the spatial location of T_2 relative to T_1 (Visser et al., 1999). Our results suggest, therefore, that spatial interactions in the AB are more complex than previously assumed.

Previous work that has suggested that T_2 can gain semantic access during the blink did so under conditions in which all stimuli, and most particularly T_1 and T_2, occurred at the same spatial location (all at fixation). Consequently, this research does not rule out the possibility that semantic access may be prevented if T_2 is presented in a different, uncertain, location (and requires online selection based on colour). Indeed, it would be most interesting to adapt the N400 ERP experiment carried out by Vogel et al. (1998) to a peripheral presentation of T_2, with a concurrent distractor (in the other visual field), to discover whether T_2 still gains access to semantics during the AB under these new presentation conditions. If the N400 was reduced, we would have strong converging evidence that the shift of attention may indeed have been suppressed by the AB. On the other hand,

it is possible that a deployment of spatial attention may not be required in order to generate an N400 response. Perhaps the N400 occurs in good readers even in the absence of a shift visual spatial attention. In any case, previous work with the N400 and the AB does not rule out an earlier locus of AB interference under conditions requiring a spatial shift in order to select and process T_2.

Another possibility is that the attentional shift, per se, was not inhibited by the AB. This view, however, requires a reinterpretation of the cognitive processes generating the N2pc. Rather than a reflection of a spatial shift, per se, the N2pc could reflect processing that takes place downstream from the shift of spatial attention. Presumably, these downstream mechanisms could not operate in the absence of the shift. In this view, the appearance of an N2pc would provide proof of a spatial shift, whereas the absence of an N2pc would not necessarily rule out a spatial shift of attention to the location of T_2. In this latter case, the N2pc would reflect processing taking place after the shift, and perhaps the AB interfered with one or more of these downstream mechanisms.

More work will be required to determine exactly what cognitive operation is reflected by the lateralised neural response that generates the N2pc. It is possible that further work combining the N2pc and the AB may help to refine our understanding of both the AB and the N2pc, and such work is presently under way in our laboratories.

The fact that the AB had only a modest impact on reports of the side on which the target colour occurred might suggest, to some readers, that attention was successfully deployed on T_2. Otherwise, how could the observers correctly report the location of the target colour? In the present context, this view would suggest that the N2pc represents processing downstream from a shift of spatial attention. We do not believe that this account is required by the results, however. We specifically used very large colour differences between the target and distractor stimuli in the T_2 frame, so as to support spatially parallel processing of the colours in the experiment (Bauer, Jolicœur, & Cowan, 1996; Nagy & Sanchez, 1990; Treisman & Gelade, 1980; Wolfe, 1994). Indeed, we implicitly assumed that the colour of T_2 would be perceived without requiring a shift of visual spatial attention, but that processing the form information at the location sufficiently to be able to identify the digit would benefit from a shift of visual-spatial attention (Luck, Fan, & Hillyard, 1993). In our view, extracting the colour and location of T_2 would take place prior to the spatial shift, and indeed this information would be required to initiate and guide the spatial shift. Consequently, we interpreted the very small AB effects on colour localization to support our hypothesis that colour information was not strongly degraded by the AB, but that the use of this information to guide visual spatial attention was likely impaired.

The SPCN, a new electrophysiological correlate of the AB phenomenon

The ERP results also revealed a new electrophysiological correlate of the AB. As can be seen in Figure 3, in addition to the N2pc, we observed a second lateralised component that was also characterised by a greater negativity contralateral to the target, between 300 ms and 500 ms. We refer to this lateralised component as a sustained posterior contralateral negativity, or SPCN. We examined the scalp distribution of the SPCN and compared it with the distribution of the N2pc, and found the two to be very similar.

This component was substantially larger for the two lag-8 conditions than the two lag-2 conditions, and onset earlier for the two ignore-T_1 conditions relative to the two report-T_1 conditions. The amplitude differences across lags reflect nicely the pattern of results we observed in the behavioural results (accuracy for T_2). This correspondence was also found in the results of Jolicœur et al. (in press), and thus it is with increasing confidence that we can begin to interpret what this component might reflect. We hypothesise that the SPCN reflects the process of encoding and maintaining T_2 in visual short-term memory (VSTM). The lateralised ERP response for this encoding process would reflect the lateralisation of T_2 itself, and converges nicely with earlier electrophysiological work on VSTM.

Klaver, Talsma, Wijers, Heinze, and Mulder (1999) documented that maintaining information in visual short-term memory produces a sustained posterior contralateral negativity relative to the side of presentation of a tobe-remembered visual shape. Vogel and Machizawa (2004) extended this work by showing that the amplitude of the SPCN increases as the number of objects in VSTM is increased, but only up to an individual observer's VSTM storage capacity. The suggestion is that the present SPCN component reflects the same neural source as the contralateral delay activity studied by Vogel and Machizawa. In our modified AB paradigm, it is possible that information that could not be reported because of the AB was also not encoded and stored in VSTM. Information may be stored in VSTM only long enough to ensure a transfer to other memory systems (e.g., verbal STM). A failure to transfer the information into VSTM would cause processing failures later in the processing stream. The SPCN in the present work (see also Jolicœur et al., in press) may reflect the neural activity that mediates the loading and maintenance of information in VSTM. This activity was delayed somewhat (in some conditions), but also clearly attenuated (Figure 3) at lag-2, where accuracy of report was the lowest. This suppression of SPCN suggests that the transfer of T_2 to VSTM suffered at lag-2 relative to lag-8. Interestingly, in the Jolicœur et al. (in press) experiment, there was no such effect of lag for the ignore-T_1 condition. The

present results thus provide further converging evidence for an effect of attentional capture by T_1, when T_1 and T_2 had the same colour.

Vogel et al. (1998) and Dell'Acqua, Jolicœur, Pesciarelli, Job, and Palomba (2003) found that the P3 response to T_2 was completely suppressed during the AB, which they interpreted as an electrophysiological indicator that a representation of T_2 could not be transferred to STM. The attenuation of the SPCN caused by the AB in the present work could well be related the suppressed P3 response during the AB that was discovered by Vogel et al. and replicated and extended by Dell'Acqua et al. In this view, not only would the AB be associated with a failure to encode information in (perhaps an amodal, or a verbal) STM store (P3 suppression), but it would also be associated with a failure of encoding in VSTM (SPCN suppression). The suppression of passage through VSTM may only occur, however, when T_2 is not at the same location as T_1, a situation in which interference with the redeployment of visual spatial attention from T_1 to T_2 may prevent efficient processing of T_2.

Although this is not the first time we have observed systematic modulations of the SPCN that correspond nicely with the behavioural AB effect, we remain cautious in our interpretations of this new component. More work will be required to establish a stronger link between VSTM and SPCN in the context of the AB. Whatever neural activity caused the SPCN, we have now replicated the observation that the component amplitude covaries with behavioural responses in the AB paradigm. Furthermore, the SPCN was delayed during report-T_1 trial blocks, suggesting that the component may be sensitive to the processing load associated with encoding T_1 into VSTM. The present results thus nicely corroborate our earlier observation that the SPCN is a new electrophysiological correlate of the AB (Jolicœur et al., in press), and suggest that further study of this component may be useful in elucidating the nature of the underlying mechanisms involved in the AB phenomenon.

REFERENCES

Bauer, B. G., Jolicœur, P., & Cowan, W. B. (1996). Visual search for colour targets that are or are not linearly-separable from distractors. *Vision Research*, *36*, 1439–1466.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 109–127.

Crebolder, J. M., Jolicœur, P., & McIlwaine, J. D. (2002). Loci of signal probability effects and of the attentional blink bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 695–716.

Dell'Acqua, R., Jolicœur, P., Sessa, P., & Turatto, M. (2006). Attentional blink and selection in the tactile domain. *European Journal of Cognitive Psychology*, *18*, 537–559.

Dell'Acqua, R., Jolicœur, P., Pesciarelli, F., Job, R., & Palomba, D. (2003). Electrophysiological evidence of visual encoding deficits in a cross-modal attentional blink paradigm. *Psychophysiology*, *40*, 629–639.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology*, *99*, 225–234.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. *Perception and Psychophysics*, *64*, 741–753.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030–1044.

Giesbrecht, B. L., & Di Lollo, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1454–1466.

Girelli, M., & Luck, S. J. (1997). Are the same attentional mechanisms used to detect visual search targets defined by color, orientation, and motion? *Journal of Cognitive Neuroscience*, *9*, 238–253.

Hopf, J.-M., Boelmans, K., Schoenfeld, A. M., Heinze, H.-J., & Luck, S. J. (2002). How does attention attenuate target–distractor interference in vision? Evidence from magnetoencephalographic recordings. *Cognitive Brain Research*, *15*, 17–29.

Jiang, J., & Chun, M. M. (2001). The influence of temporal selection on spatial selection and distractor interference: An attentional blink study. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 664–679.

Jolicœur, P. (1999). Concurrent response selection demands modulate the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1097–1113.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, *36*, 138–202.

Jolicœur, P., & Dell'Acqua, R. (2000). Selective influence of second target exposure duration and Task$_1$ load effects in the attentional blink phenomenon. *Psychonomic Bulletin and Review*, *7*, 472–479.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (in press). On the control of visual spatial attention: Evidence from human electrophysiology. *Psychological Research*.

Klaver, P., Talsma, D., Wijers, A. A., Heinze, H.-J., & Mulder, G. (1999). An event-related brain potential correlate of visual short-term memory. *NeuroReport*, *10*, 2001–2005.

Luck, S. J., Fan, S., & Hillyard, S. A. (1993). Attention-related modulation of sensory-evoked brain activity in a visual search task. *Journal of Cognitive Neuroscience*, *5*, 188–195.

Luck, S. J., Girelli, M. T., McDermott, M. A., & Ford, M. A. (1997). Bridging the gap between monkey neurophysiology and human perception: An ambiguity resolution theory of visual selective attention. *Cognitive Psychology*, *33*, 64–87.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 1000–1014.

Nagy, A. L., & Sanchez, R. R. (1990). Critical color differences determined with a visual search task. *Journal of the Optical Society of America*, *7*, 1209–1217.

Miller, J., Paterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differenes. *Psychophysiology*, *35*, 99–115.

Pinker, S. (1984). Visual cognition: An introduction. *Cognition*, *18*, 1–63.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 979–992.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 849–860.

Seiffert, A. E., & Di Lollo, V. (1997). Low-level masking in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *23*, 1061–1073.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*, 1–29.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual task performance. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 3–18.

Treisman, A. M., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, *12*, 97–136.

Ulrich, R., & Miller, J. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology*, *38*, 816–827.

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attentional switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin*, *125*, 458–469.

Vogel, E. K., Luck, S. J., & Shapiro, K. L. (1998). Electrophysiological evidence for a postperceptual locus of suppression during the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 1656–1674.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748–751.

Von Wright, J. M. (1972). On the problem of selection in iconic memory. *Scandinavian Journal of Psychology*, *13*, 159–171.

Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, *1*, 202–238.

Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *29*, 121–138.