



Electrophysiological evidence of multitasking impairment of attentional deployment reflects target-specific processing, not distractor inhibition

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ABSTRACT

We studied the interaction between the control mechanisms subserving spatial attention and central attention using the psychological refractory period (PRP) paradigm. Two stimuli, a pure tone (T_1) and a circular visual array (T_2), including a salient target and a salient distractor, were presented at varying stimulus onset asynchronies, each requiring a speeded response. Target-specific and distractor-specific lateralized event-related potentials were isolated by placing one of them at a lateral position and the other on the vertical midline. As SOA was decreased, a progressive reduction and postponement of a T_2 -locked N2pc component was observed with a lateral target and a central distractor. No lateralized potentials were associated with a lateral distractor and a central target. The sustained posterior contralateral negativity (SPCN) was observed independently of SOA modulation, only with a lateral target. We also observed an earlier positive deflection, the Ppc (positivity posterior contralateral), that was contralateral to both lateral targets and distractors, whose amplitude and latency were not affected by SOA variations. We conclude that central processing interferes specifically with target processing reflected by the N2pc and SPCN. We propose that the Ppc reflects an initial, bottom-up response to the presence of a salient stimulus, whereas the N2pc and SPCN reflect the controlled deployment of spatial attention to targets and maintenance of target information in visual short-term memory, respectively.

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1. Introduction

The goal of this work was to study interactions between the control mechanisms subserving two putatively different forms of attention, spatial attention and central attention (Johnston et al., 1995; Pashler, 1991). Spatial attention mechanisms are commonly assumed to operate as a filter that prevents perceptual information from overloading later, capacity-limited memory stages, such as visual short-term memory (e.g., Cowan, 2001; Sperling, 1960). Central attention mechanisms are hypothesized to receive this selectively attended information and execute, if required, different forms of processing (e.g., selection of an appropriate response, encoding the information into memory; Jolicœur and Dell'Acqua, 1998). Although many studies have shown

that visual spatial attention can enhance early sensory/perceptual stages of processing and that information processed at later, capacity-limited, central stages is based on selected representations, other aspects of the relationship between them are still unclear (Brisson and Jolicœur, 2007a). In fact, in contrast to the hypothesis of a functional dissociation of these forms of attention, more recent evidence has challenged this view by suggesting overlap between them (e.g., Jiang and Chun, 2001; Brisson and Jolicœur, 2007a, 2007b; Jolicœur et al., 2006a, 2006b).

The psychological refractory period paradigm (PRP) has been used extensively to study the limits of attention during multitasking. In this paradigm, two successive targets, T_1 and T_2 , are displayed at varying stimulus onset asynchronies (SOAs), often in different sensory modalities. The tasks usually involve a speeded n -alternative discrimination to each target, thereby producing two response times, RT_1 and RT_2 . On the premise that both tasks require central attention, which can be allocated serially to only one stimulus at a time, the typical finding is a PRP effect, namely, a progressive increase in RT_2 as SOA is decreased, with RT_1 usually much less affected by SOA (but see Tombu and Jolicœur, 2003). Furthermore, when the time required to carry out response selection for $Task_1$ is systematically prolonged (e.g., by increasing the number of response alternatives to T_1), the

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resultant increase in RT_1 is accompanied, at short SOA, by a corresponding increase in RT_2 , suggesting that response selection is sometimes a critical operation requiring central attention (Pashler, 1994).

Although much evidence has linked dual-task interference to central attention, new evidence suggests that dual-task interference sometimes takes place relatively early in processing. Results linking PRP-like interference and the deployment of visual spatial attention have come from studies focusing on the N2 posterior contralateral (N2pc) component of the event-related potential (ERP; Brisson and Jolicoeur, 2007a, 2007b; Brisson et al., 2009). The N2pc is a lateralized ERP component that is generally accepted to be an index of selective stimulus processing and has been used to track the deployment of attention in a variety of different paradigms (e.g., Woodman and Luck, 2003). It is characterized by enhanced negativity at occipito-parietal electrode sites contralateral to the visual hemifield containing an attended item, relative to activity recorded over the ipsilateral scalp. Typically, the N2pc occurs 180–280 ms after target onset (e.g., Dell'Acqua et al., 2006; Brisson and Jolicoeur, 2007a, 2007b; Luck and Hillyard, 1994a, 1994b) and appears to originate predominantly in lateral portions of the visual extrastriate cortex (Hopf et al., 2000). In PRP studies, a progressive amplitude reduction of the N2pc elicited in response to a visual T_2 display containing a lateral target was observed as the T_1 – T_2 SOA was decreased (Brisson and Jolicoeur, 2007a, 2007b). These results provided strong evidence that the deployment of visual spatial attention was disrupted by dual-task interference. This, in turn, suggested that the control mechanisms mediating the deployment of visual spatial attention overlap with those mediating dual-task performance.

Although there is general agreement that N2pc reflects visual selection, there has been debate as to whether it is associated with target processing, distractor suppression, or both. Some results suggested that distractor suppression may play a special role in the generation of the N2pc (Luck et al., 1997; Luck and Hillyard, 1994a). For example, the N2pc was found to be larger when a to-be-attended target was accompanied by a salient distractor (Luck et al., 1997). Other studies suggested that N2pc reflects a process of target enhancement, rather than of distractor suppression (e.g., Eimer, 1996; see also Hilimire et al., 2009). In many cases, it is impossible to determine whether the observed N2pc is due to target processing or distractor suppression. This is especially true when balanced visual displays containing a relevant target singleton and a similar, but irrelevant, distractor singleton on opposite sides of fixation are used to elicit N2pc. Such balanced arrays rule out low-level sensory contributions to N2pc, or any other lateralized ERP component that may be observed, but they confound ERP lateralizations tied to the target and to the distractor on either side of fixation. In particular, a target-related N2pc might reflect a negativity contralateral to the target, a positivity contralateral to the distractor, or some combination of these two hypothetical sub-components (Hickey et al., 2009).

Hypothetical sub-components of N2pc can be isolated by presenting one of the two critical items at a lateral location and the other at a location above or below fixation on the vertical midline. The stimulus on the midline presumably does not activate the hemispheres differentially depending on the position of a lateral stimulus used to define what is ipsilateral and what is contralateral, and so its contribution to N2pc defined relative to a lateral stimulus would cancel out, even when that item is attended (Woodman and Luck, 2003). Therefore, it is possible to attribute lateralized ERP activities to the other, lateral item in such displays. Using this approach, Hickey et al. (2009) argued that lateral targets elicit a contralateral negativity (N_T) whereas lateral distractors elicit a contralateral positivity (P_D). They speculated that the N2pc observed using balanced displays would reflect the sum of these two opposite-polarity components. According to Hickey et al. (2009), lateral distractors elicit a

lateralized positivity, P_D , component at about 230–280 ms post stimulus onset, at the posterior contralateral scalp relative to the visual hemifield in which a distractor was presented. They argued that the P_D is associated to the attentional suppression process of a localized distractor. On the other hand, lateral targets would elicit a lateralized negativity, N_T , component elicited at about 175–325 ms post-stimulus, at the posterior contralateral scalp relative to the visual hemifield to which the target was presented. Similar to the N2pc, the N_T would be associated with the amplification of the cortical representation of an attended target. Hickey et al. (2009) suggested that selection in visual search starts with a process related to the target processing (onset at about 175 ms) and progresses to include a later process of distractor suppression (onset at about 230 ms). The present experiment in principle allowed us to examine PRP effects separately for the N_T and P_D in a way that was not possible in the investigations of Brisson and Jolicoeur (2007a, 2007b) who used the typical balanced displays containing opposite-hemifield targets and distractors.

In this paper, we focused on the processing of salient targets and distractors in displays in which one of them was lateral and one was on the vertical midline. As anticipated, this technique enabled us to separate out lateralized brain activity related to target processing from activity related to the distractor. We examined this in the context of the PRP paradigm in order to determine unequivocally whether the N2pc amplitude reduction observed at short SOA in prior, analogous PRP work (Brisson and Jolicoeur, 2007a, 2007b; Brisson et al., 2009) was due to target-related processing, distractor-related processing, or some combination of the two.

In the present work we also examined another lateralized ERP component, the sustained posterior contralateral negativity (SPCN) that often follows the N2pc. This component has been linked to the active maintenance of information in visual short-term memory (e.g., Jolicoeur et al., 2008; Luria et al., 2010; Vogel and Machizawa, 2004), and shown to be dissociable from the N2pc (Jolicoeur et al., 2008). One would expect to observe a clear SPCN following successful encoding of a lateral target, on the assumption that temporary buffering in visual short-term memory of the target, for response selection purposes, was required in the present design. In contrast, we did not expect an SPCN, in response to lateral distractors in the present circumstances, because memory buffering of stimuli that can be filtered out early in processing on the basis of color should not occur for clear distractors. Previous work suggests that multitasking interference can delay the onset of the SPCN, suggesting a delayed encoding into visual short-term memory (Brisson and Jolicoeur, 2007b). This should only be observed for lateral targets and not for lateral distractors if target selection takes place before entry into visual short-term memory.

In this present PRP design, T_1 was a pure tone at one of four possible pitches. Task₁ was to indicate the pitch of T_1 rapidly via button press. T_2 was a visual stimulus, a color singleton that contained an oriented line. Task₂ was to respond on the basis of the orientation of the line, as rapidly as possible, via button press. T_2 was either red or green and was accompanied by a different-color singleton distractor (red if T_2 was green, or green if T_2 was red). In half of the trials, T_2 was lateral and the distractor was on the vertical midline, enabling an examination of target-related lateralized activity. In the remaining trials, the distractor was lateral and the target was on the midline, enabling an examination of distractor-related lateralized activity. The SOA between T_1 and T_2 was manipulated systematically so as to measure effects of task overlap on target-related and distractor-related processing.

We predicted that a target-related contralateral negativity (N2pc/ N_T) would be observed when the target was lateral, and that the amplitude of this response would decrease as the T_1 – T_2 SOA was reduced. Furthermore, the onset of the SPCN in this condition should be delayed as SOA was reduced. Such results would suggest that a significant portion of the previous results of Brisson and Jolicoeur were a reflection of target-related processing. In the conditions with a

lateral distractor, our aim was to discover whether a distractor-related contralateral positivity (P_D) would be observed, and if this component was also attenuated by decreasing SOA. The presence of a P_D in the present study was not however taken for granted because of the many significant differences in display characteristics between the present stimuli and those of Hickey et al. (2009). Because distractors need not be processed beyond what is needed to prevent them from influencing the response, we predicted that there should be no SPCN when the distractor was lateral, which would suggest that a representation of the salient distractor was successfully prevented from entering visual short-term memory.

2. Experiment

2.1. Method

2.1.1. Participants

Forty undergraduate students from Université de Montréal participated in this experiment for financial compensation (20\$ CAN). Data from fifteen participants had to be discarded because less than 50% of trials in at least one SOA condition remained after artifacts rejection or because they were grouping responses (see Pashler and Johnston, 1989). For grouping responses, we calculated the interresponse time (IRT) as shown in Ulrich and Miller (2008) and we rejected the participants with an IRT of less than 200ms. Twenty-five participants (6 males; 2 left handed; mean age: 23.12 ± 3.69) remained in the final sample. All participants were neurologically intact and reported having normal hearing, normal color vision, and normal or corrected-to-normal visual acuity.

2.1.2. Stimuli

For each trial, a 100 ms tone (T_1), presented to both ears by pneumatic earphones was followed at a randomly-selected temporal delay (SOA of 150ms, 450ms, or 950ms) from trial to trial, by a 200ms visual display that contained the second target (T_2), as illustrated in Fig. A.1. T_1 could be at one of four frequencies (200Hz, 430.9Hz, 928.3Hz, or 2000Hz). T_2 was presented in a circular visual search array consisting of ten small circles each presented 4.0° from the central fixation point. Two of these smaller circles were situated on the vertical meridian and four were situated on each side of the fixation point. The circles (1.5° in diameter) were drawn with a thin (0.05°) red, green, or gray outline. Each circle contained a line ($0.6^\circ \times 0.05^\circ$) in one of four orientations (vertical, horizontal, left oblique, right oblique). The orientation of the line inside the T_2 circle varied randomly from trial to trial. The fixation point had a diameter of 0.12° .

Two of the ten circles were colored, either red or green, and the remaining 8 were gray, and their luminance was approximately equal (25 cd/m^2) and they were presented on a black background (0.25 cd/m^2).

2.1.3. Procedure

Participants sat in a dimly lit, electrically shielded room, facing a computer screen, at a viewing distance of 57cm. The participants heard the four tones from low to high frequencies as many times as they wanted after being informed of the task instructions. Then, participants performed one practice block of 24 trials followed by 8 experimental blocks of 96 trials. Each trial was initiated by pressing the space bar. Feedback from the preceding trial disappeared and a fixation point simultaneously appeared at the center of the computer screen, which was visible throughout the remainder of the trial. The onset of T_1 occurred between 400 and 600ms later (random jitter using a rectangular distribution). A tone (T_1) was presented (all tone frequencies were randomly presented equally often in each block and randomly presented from trial to trial), followed at an SOA of 150, 450 or 950ms by a visual display that contained T_2 (all

combinations of T_1 frequency, SOA, and T_2 orientation were presented equally often, in random order, in each block).

Two separate four-choice speeded responses were required on each trial. The first response was to the pitch of T_1 and the second response was to the orientation of the line in one of the colored circles (T_2). The target (T_2) was red and the distractor was green for half of the participants and inversely for the other half. Responses to T_1 were made with fingers of the left hand (adjacent response keys arrayed from left to right: little finger, ring finger, middle finger, index finger), “Z”, “X”, “C” or “V” for the 200Hz, 430.9Hz, 928.3Hz, or 2000Hz tone, respectively) and responses to T_2 were made with fingers of the right hand (index, middle, ring, little finger) (response keys were “N”, “M”, “,” or “.” for left oblique, vertical, horizontal, or right oblique, respectively). Instructions emphasized the importance of responding as quickly and accuracy as possible to T_1 as soon as T_1 was presented and of responding as quickly and accuracy as possible to T_2 as soon as T_2 was presented. The participants had 3000ms to respond for each task.

Trials ended with the simultaneous disappearance of the fixation point and appearance of the visual feedback, 3000ms after the presentation of T_2 (the duration of feedback was 500ms). Immediately to the left of the center of the screen, a “+” or “-” indicated a correct or incorrect response to T_1 , respectively. Immediately to the right of the center of the screen, a “+” or “-” indicated a correct or incorrect response to T_2 . In both cases, a vertical bar (“|”) appeared if the participants took too much time to answer. Participants were instructed to maintain central eye fixation throughout the trial and blink only when the feedback was on the screen.

2.1.4. EEG recording and analysis

The EEG was recorded from 64 active Ag/AgCl electrodes (Biosemi Active Two system) mounted on an elastic cap and referenced to the average of the left and right mastoids. Electrodes were placed according to the 10–10 system (Sharbrough et al., 1991) at Fp1, Fp2, Fp7, Fp8, AF7, AF3, AFz, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP5, CP3, CP1, CPz, CP2, CP4, CP6, TP8, P9, P7, P5, P3, P1, Pz, P2, P4, P6, P8, P10, PO7, PO3, POz, PO4, PO8, O1, Oz, O2, and Iz sites. The horizontal electrooculogram (HEOG) recorded as the voltage difference between electrodes placed lateral to the external canthi was used to measure horizontal eye movements. The vertical electrooculogram (VEOG), recorded as the voltage difference between two electrodes placed above and below the left eye, was used to detect eye blinks. Signals were recorded at a sampling frequency of 512Hz from DC to 134Hz. A bandpass filter of 0.01–40Hz was applied during post-recording processing.

Trials with eye blinks (VEOG $> 50 \mu\text{V}$), large horizontal eye movements (HEOG $> 40 \mu\text{V}$), and/or artifacts at electrode sites of interest (i.e., $> 100 \mu\text{V}$ at O1, O2, PO7, PO8, P7, and/or P8 electrode sites on 50ms intervals) were rejected. Fifteen participants were excluded because more than 50% of trials were rejected in at least one experimental condition based on these criteria or because they were grouping responses (see Pashler and Johnston, 1989) (see subjects section). Of the remaining 25 participants, an average of 90% of 150ms SOA trials, 91% of 450ms SOA trials, and 92% of 950ms SOA trials remained after artifact rejection. None of these participants had residual eye movements that deviated more than 0.2° (i.e., average HEOG was $< 3.2 \mu\text{V}$ at all times for left or right target location) toward T_2 after rejection criteria were applied (see Luck, 2005).

The EEG was averaged starting 200ms prior to the T_2 onset and ending 1000ms after T_2 onset, and baseline-corrected based on average activity recorded during the 200ms preceding T_2 onset. The ipsilateral waveform (average of left-sided electrode with left visual field T_2 and right-sided electrode with right visual field T_2) and contralateral waveform (average of left-sided electrode with right visual field T_2 and right-sided electrode with left visual field T_2) time-locked to

T_2 for all SOA conditions at PO7/PO8 electrode sites were computed separately. Event-related lateralizations (ERLs) were quantified following the subtraction of the ipsilateral waveforms from the contralateral waveforms.

We quantified various ERL components as follows. To isolate a possible P_D response to lateral distractors (when the T_2 was on the vertical midline), we computed the mean amplitude of the ERL during a window of 280–330ms post-visual-display. T_2 -related ERL (corresponding in principle to the N_T subcomponent of N2pc) was calculated by considering trials on which the distractor was on the midline and the target was lateral. These ERLs were quantified as the mean amplitude of the ERL in a window of 230–260ms. We also examined an earlier positivity contralateral to the lateral salient stimulus that we call the positivity posterior contralateral (Ppc) as well as the component following the N2pc, the SPcN, and the P_D . The Ppc was quantified as the mean of the ERL in a window of 130–160ms post onset of the visual display for lateral target condition and for lateral distractor condition. SPcN was quantified as the mean amplitude of the ERL during the 600–700ms post visual display time window for relevant conditions and was obtained from the subtraction waveforms. For each of these four components (P_D , N2pc/ N_T , Ppc, and SPcN) we examined signals for each of the three SOAs conditions (150ms, 450ms, 950ms) at PO7/PO8 electrode sites. Amplitude measures were obtained for each of these grand average waveforms and the value was submitted to an analysis of variance (ANOVA). A Greenhouse–Geisser correction for non-sphericity was applied when appropriate. Bonferroni corrections for multiple post-hoc comparisons were used when appropriate.

Also, onset latency measurements were obtained using a jackknife method (Kiesel et al., 2008; Miller et al., 1998; Ulrich and Miller, 2001). With the jackknife method, n grand average waveforms are computed, each with $n - 1$ participants, by removing a different participant for each jackknife waveform. Latency measures are obtained for each of these n grand average waveforms, and the values are submitted to a conventional analysis of variance (ANOVA), but for which the F values are adjusted to compensate for the reduced variance across jackknife averages using the equation proposed by Ulrich and Miller (2001), namely $F_{\text{adjusted}} = F / (n - 1)^2$.

3. Results

3.1. Behavior

Behavioral data (mean percent accurate responses and RT for Task₁ and Task₂) and electrophysiological measures were submitted to separate repeated measures ANOVAs in which SOA (150ms, 450ms, or 950ms) was treated as a within-subject factor. Only trials with correct responses to both T_1 and T_2 were included in the reaction time (RT) analyses to T_2 , and outliers were excluded using the method described in Van Selst and Jolicoeur (1994). Behavioral and ERP analyses were conducted on the remaining data.

Table A.1 presents mean RTs and percentage of correct responses observed in Task₁ and Task₂ as a function of SOA. Mean accuracy in Task₁ was 80.1% (SD=5.22%). Accuracy in Task₁ increased as SOA was increased ($F(2, 48) = 28.50, p < .0001$). Mean accuracy in Task₂ was 92.0% (SD=4.49%) overall. Accuracy in Task₂ also increased as SOA was increased ($F(2, 48) = 30.24, p < .0001$).

Mean RT₁ did not vary significantly across SOA, $F(2, 74) = 1.54, p > .22$. As expected, however, mean RT₂ increased as SOA was reduced, $F(2, 74) = 14.43, p < .0001$, showing the expected PRP effect.

3.2. Electrophysiology

3.2.1. Ppc

A positive deflection contralateral to salient stimuli was observed in the ERL waveforms for both the lateral target (Fig. A.2a) (in a window of

130ms to 160ms at PO8/PO7 electrodes) and the lateral distractor condition (Fig. A.2b). The scalp distribution of this component, which we call the Ppc is shown in Fig. A.3b.

An analysis of variance (ANOVA) was performed on the mean amplitude of the Ppc (in a window of 130–160ms at PO8/PO7 electrodes for the lateral target condition and for the lateral distractor condition) with two within-subjects factors: target vs. distractor (as the lateral stimulus) and SOA. We found no effect of SOA on Ppc mean amplitude, $F(2, 48) = 0.50, p > .60$, and no difference between the target vs. distractor conditions, $F(1, 24) = 1.80, p > .19$, and there was no interaction between the two factors, $F < 1$. The presence of the Ppc was established by performing a t -test against 0 on the overall mean amplitude of the Ppc across all conditions, $t(24) = 4.24, p < .0001$. In fact, the Ppc waveforms were significantly different from 0 in all cases according to a t -test against zero for each SOA condition separately for target trials (150ms SOA, $t(24) = 2.44, p < .023$; 450ms SOA, $t(24) = 3.88, p < .001$, and 950ms SOA, $t(24) = 2.23, p < .035$), and for distractor trials (150ms SOA, $t(24) = 2.6, p < .016$; 450ms SOA, $t(24) = 3.3, p < .003$; and 950ms SOA, $t(24) = 2.25, p < .035$). To correct for multiple comparisons, we adopted the Benjamini and Hochberg (1995) approach to control for False Discovery Rate (FDR; q -value = .05). According to this approach, all the t -tests against 0 were significant while holding the FDR at .05 or less (see also Howell, 2010).

We also examined the latency of the onset of the Ppc using a jackknife method (Miller et al., 1998; Ulrich and Miller, 2001) to evaluate possible SOA effects in the target condition (see Fig. A.2a). The latency at which waveforms reached $0.2\mu\text{V}$, starting at 50ms after the visual display, was estimated from jackknife average waves and submitted to ANOVA. This analysis revealed no main effect of SOA on the onset latency of the Ppc after the adjustment proposed by the Ulrich and Miller, ($F_{\text{adjusted}}(2, 48) = 0.15, p > .86$). Furthermore, a jackknife analysis computed for different SOAs in the distractor condition (see Fig. A.2b) for the latency at which the Ppc reached $0.2\mu\text{V}$ (starting at 50ms) also failed to reach significance $F_{\text{adjusted}}(2, 48) = 0.15, p > .86$. These results show that Ppc component was equally elicited by a lateralized target or by a lateralized distractor, and that it was not influenced by the temporal delay (SOA) between stimuli for the two tasks.

3.2.2. N2pc

Fig. A.2a shows the grand average ERL waveforms at PO7/PO8 (contralateral minus ipsilateral), time-locked to the onset of T_2 , for each SOA between T_1 and T_2 when the target was lateral and the distractor was on the vertical midline. The scalp distribution of the lateralized electric potentials for the N2pc time window for each SOA is shown in Fig. A.3a. An analysis of variance (ANOVA) performed on the mean amplitude of the N2pc (in a window of 230–260ms), which was the first large negative deflection in the ERL subtraction waveforms. As expected from Fig. A.2a, there was a systematic attenuation of the N2pc amplitude as SOA was reduced, $F(2, 48) = 7.73, p < .002$. Bonferroni-corrected post-hoc tests revealed a significant difference between each possible pair of SOA conditions. We also examined the latency of the onset of the N2pc as a function of SOA using a jackknife method (Kiesel et al., 2008; Miller et al., 1998; Ulrich and Miller, 2001). The latency at which waveforms reached $-0.8\mu\text{V}$, starting at 100ms after the visual display, was estimated from jackknife average waves and submitted to ANOVA. This analysis revealed a main effect of SOA on the onset latency of the N2pc, $F_{\text{adjusted}}(2, 48) = 16.43, p < .0001$. Thus, the N2pc wave started earlier when the T_1 – T_2 SOA was long and N2pc decreased in amplitude as SOA was reduced. Bonferroni's post-hoc test revealed a significant difference between short and middle SOA conditions, between long and short SOA conditions and between middle and long SOA conditions. These results nicely dovetail with the amplitude effects, and suggest that multitasking can sometimes

both delay and attenuate the amplitude of the N2pc for a lateral target.

An ANOVA performed on the mean amplitude of the N2pc (in a window of 230–260ms) in the lateral distractor condition revealed no interaction of SOA condition, $F(2, 48) = .178, p < .84$. Furthermore, no N2pc was found in the lateral distractor condition, according to a *t*-test against zero for each SOA condition separately (150ms SOA, $t(24) = -1.03, p < .31$; 450ms SOA, $t(24) = -.85, p < .40$; and 950ms SOA, $t(24) = -1.74, p < .09$) and so these results were not analyzed further.

3.2.3. SPCN

As illustrated in Fig. A.2a, the N2pc was followed by a sustained posterior contralateral negativity (SPCN) that appeared to have been delayed at shorter SOAs. An ANOVA on the mean amplitude of the SPCN in a time window of 600–700ms did not reveal a significant effect of SOA, $F(2, 48) = .16, p > .21$. However, the SPCN waveforms were significantly different from 0 in all cases according to a *t*-test against zero for each SOA condition separately for target trials (150ms SOA, $t(24) = -3.48, p < .002$; 450ms SOA, $t(24) = -3.29, p < .003$, and 950ms SOA, $t(24) = -3.45, p < .002$). Then, a *t*-test against zero for each SOA condition separately for target trials was calculated in a time window of 480–550ms and revealed SPCN waveforms different from 0 only in 450 and 950ms SOA condition (150ms SOA, $t(24) = -1.26, p > .22$; 450ms SOA, $t(24) = -2.27, p < .03$; and 950ms SOA, $t(24) = -2.21, p < .03$). These results suggest that the onset of the SPCN was delayed in the 150ms SOA condition, relative to the other SOA conditions, as found previously in Brisson and Jolicoeur (2007a, 2007b, 2007c). However, the SPCN waveforms were not significantly different from 0 according to a *t*-test against zero for each SOA condition separately for target trials in a time window of 400–480ms (150ms SOA, $t(24) = .24, p < .81$; 450ms SOA, $t(24) = -.70, p < .49$, and 950ms SOA, $t(24) = -1.37, p < .19$). These results were not significant because of the large variability between participants. Furthermore, a jackknife analysis of the latency at which the SPCN reached $-0.5\mu\text{V}$ starting at 450ms after the visual display also failed to reach significance $F_{\text{adjusted}}(2, 48) = 0.04, p > .96$. Thus, although the onset of the SPCN waves was numerically delayed in the same fashion as in previous work as SOA was reduced, the effects were not significant in the present work (see Brisson and Jolicoeur, 2007a, 2007b, 2007c). Given that there was no clear SPCN in the lateral distractor condition (as expected by inspection of Fig. A.2b), according to a *t*-test against zero for each SOA condition separately (150ms SOA, $t(24) = -.97, p < .344$; 450ms SOA, $t(24) = .32, p < .754$; and 950ms SOA, $t(24) = -.006, p < .995$), these data were not subjected to further analysis.

3.2.4. P_D

A *t*-test against zero was performed on the mean amplitude of the P_D (in a window of 280ms to 330ms). No P_D was found in the lateral distractor condition for each SOA condition separately (150ms SOA, $t(24) = -.69, p < .498$; 450ms SOA, $t(24) = .96, p < .346$; and 950ms SOA, $t(24) = .78, p < .446$). So, these data were not subjected to further analysis.

4. Discussion

Our goal was to evaluate interactions between the control mechanisms subserving spatial attention and central attention and to do so separately for processing of lateral targets or lateral distractors. We used a dual-task paradigm in which the second display engaged visual spatial attention with displays and a task known to elicit the N2pc, as well as the SPCN (when the display contained a lateral target). By presenting either the target or the distractor in a lateral position or on the vertical midline, in the context of a PRP paradigm, our work was the first to enable a separate examination of dual-task

(PRP) interference on visual spatial processing of salient targets or distractors.

In the lateral target condition, the distractor was on the vertical midline and the target was lateral, which enabled us to observe a clear posterior contralateral negativity, likely the N2pc (or perhaps the N_T portion of the N2pc), elicited by the lateral target (with a peak at about 240ms post-stimulus; Hickey et al., 2009; Luck and Hillyard, 1994a). The major findings were that the target-specific N2pc was significantly attenuated by dual-task interference, as shown by the reduction of the amplitude of the N2pc as the SOA between T₁ and T₂ was reduced. These results suggest strongly that concurrent central processing (of a tone) interferes with the deployment of visual-spatial attention to a lateral target. These results extend those reported by Brisson and Jolicoeur (2007a, 2007b, 2007c) by showing that this effect can be observed under conditions that isolate target-related processing, *per se*. These results converge nicely with those of Brisson and Jolicoeur (2007a, 2007b, 2007c) and suggest that PRP interference occurs not only at late stages of processing, such as response selection, but also at earlier stages involved in target selection. In the present work, N2pc was both attenuated and delayed as dual-task interference increased (as SOA was reduced).

Although the N2pc amplitude was attenuated as SOA decreased, no such effect was found in the case of the SPCN. This finding suggests that the target was successfully encoded into visual short-term memory for later processing regardless of the temporal delay between the two stimuli. This pattern of results is consistent with the high accuracy in Task₂ at all SOAs, unlike what is found in the attentional blink paradigm (see Jolicoeur et al., 2006ab). The AB paradigm can be observed in a context of dual-task paradigms in which two targets are presented in rapid succession, typically within a rapid serial visual presentation (RSVP) of nontargets (Raymond et al., 1992; Shapiro et al., 1997). The Task₂ stimuli are masked by preceding and trailing nontargets. This paradigm is characterized by a reduced report accuracy for the second target (T₂) when the temporal delay between T₁ and T₂ is shorter (Cousineau et al., 2006). This is not surprising given that Task₂ stimuli were not masked in the present study, but are typically masked in the AB paradigm. The absence of SOA effects on SPCN amplitude is thus consistent with the behavioral accuracy results for Task₂. Furthermore, the difference of modulation patterns between the N2pc component and the SPCN component shows that these two components reflect different cognitive functions (as argued by Jolicoeur et al., 2008).

This present study replicates only partially those observed in Brisson and Jolicoeur (2007a, 2007b, 2007c) because the SOA condition effects on the latency of SPCN onset did not reach statistical significance (although they were numerically in the previously-observed order). It is possible that the less stable statistical results for the latency effects of SOA on the SPCN reflect the fact that the distractor was not lateral when the target was lateral, which may have facilitated passage of the lateral target into VSTM, once selected. Importantly, the lateral distractor condition did not elicit an SPCN component. This suggests that subjects were able to select stimuli on the basis of color and to exclude unwanted stimuli from further processing, to the advantage of desired targets.

In both the lateral target and the lateral distractor trials, we observed an early posterior contralateral positivity (Ppc) component at about 130–160ms post-stimuli. Given that the Ppc was present for both targets and distractors, but the N2pc was only observed for targets, the suggestion is that the Ppc reflects attentional selection of a stimulus based on the presence of a color difference across stimuli (here red or green, relative to less salient gray distractors), prior to selection that would be based on a particular color value (red vs. green in this case). The Ppc may thus represent the creation of a signal in an initial attentional salience map (e.g., Wolfe, 1994) that would be followed by a more refined selection leading to the N2pc

for targets, which would then lead to an SPN when the selected stimulus enters visual short-term memory. Given that the Ppc appeared to be independent of the specific color generating the color difference relative to background items, it is possible that differences in the color dimension, as a whole, were prioritized. This account is consistent with the feature dimension weighting account of visual search for targets, suggested by Müller and collaborators (e.g., Müller et al., 2003; Found and Müller, 1996). In the present experiment, participants knew the color of the target before the beginning of each trial. This knowledge of the target-defining dimension may have biased attentional mechanisms by allocating more attention to a specific dimension (here color) allowing the subject to be more efficient in subsequent search for a particular feature value on this dimension. Interestingly, the Ppc was not influenced by SOA, suggesting that the initial selection based on a color versus gray local feature discontinuity did not require a capacity-demanding attentional process (at least, not one that overlaps with central attentional mechanisms engaged by the particular Task₁ we used in our PRP paradigm).

Results found in this work are different from those of Sawaki and Luck (2010) who also purported to study the P_D and N2pc components. Sawaki and Luck (2010) used a cueing task in which the participant had to pay attention to the upper or the lower visual field. In the attended area, participants were instructed to detect a previously designated target (e.g., a large A). Sawaki and Luck (2010) found that a P_D (positivity contralateral to a distractor) component could be elicited by a salient or nonsalient distractor, and was not found when a salient stimulus was a target. Their component was elicited whether the distractor occurred in the to-be-attended area or in the to-be-ignored area, with a latency in the 115–225 ms range. In the present work, the Ppc component occurred in a similar temporal interval as the P_D component of Sawaki and Luck (2010), however, the Ppc component did not vary depending on the status of the salient stimulus as a target or distractor. More focused studies will be necessary to determine the relationship between the component studied by Sawaki and Luck (2010) and our Ppc.

One unexpected finding in the present study was that we found no clear P_D when a salient distractor was lateral (and the target was on the midline). Based on the work of Hickey et al. (2009), we expected this condition to reveal a clear P_D, and our goal was to examine how the P_D behaved under different degrees of PRP interference (via the manipulation of SOA). As such, the present results show that we do not understand the conditions required to observe a clear P_D component. A possible explanation of the absence of the P_D was the more difficult attentional context in the present work, created by the need to perform two distinct tasks (in contrast with single-task conditions in the Hickey et al., 2009, study). Perhaps the control over

distractor processing was decreased, resulting in reduced distractor inhibition, which was not enough to elicit a distinct P_D component. Another possibility is that we embedded the salient distractor among several less salient (gray) distractors, unlike Hickey et al. (2009) who had many fewer simultaneous stimuli in the visual field. Perhaps the presence of numerous distractors spread out the suppression postulated by Hickey et al. (2009) to all distractors, leading to greater left-right balance in distractor suppression and an absence of visible contralateral positivity relative to the location of the most salient distractor. However, the absence of a clear P_D to lateral distractors cannot be attributed to ineffectual distractor suppression because salient lateral distractors elicited neither an N2pc nor an SPN, at all SOAs. The salient distractor was thus clearly excluded from attended processing at later stages of processing (perhaps because not actively selected). Whatever the reasons, under present display and task conditions, we found no evidence for a positivity contralateral to a salient distractor, suggesting some important boundary conditions for the phenomenon investigated by Hickey et al. (2009).

Results of the present study suggest that the influence of dual-task (PRP) interference on visual spatial attention deployment reflect primarily interference on mechanisms related to target processing. At the same time, we did not find evidence for mechanisms specifically related to distractor suppression. Importantly, because previous studies relating dual-task (PRP) interference and visual-spatial processing used visual displays that shared many of the characteristics of the present displays. The evidence suggests strongly that previous findings of dual-task interference on the N2pc reflected primarily interference on target-related processing, with little or no contribution from possible mechanisms of distractor suppression. More research will be needed to determine if it is possible to create conditions conducive to the observation of dual-task interference with possible mechanisms of distractor suppression.

Appendix A

Table A.1

Mean percentage of correct responses and reaction time (RT) to T₁ and T₂ for each SOA (standard deviation in parentheses).

SOA (ms)	RT ₁	Accuracy ₁	RT ₂	Accuracy ₂
150	1076 (200)	87.8 (5.57)	1358 (357)	91.5 (3.87)
450	1051 (224)	88.8 (5.23)	1141 (226)	93.0 (3.69)
950	1169 (311)	90.0 (4.57)	953 (186)	93.5 (3.67)

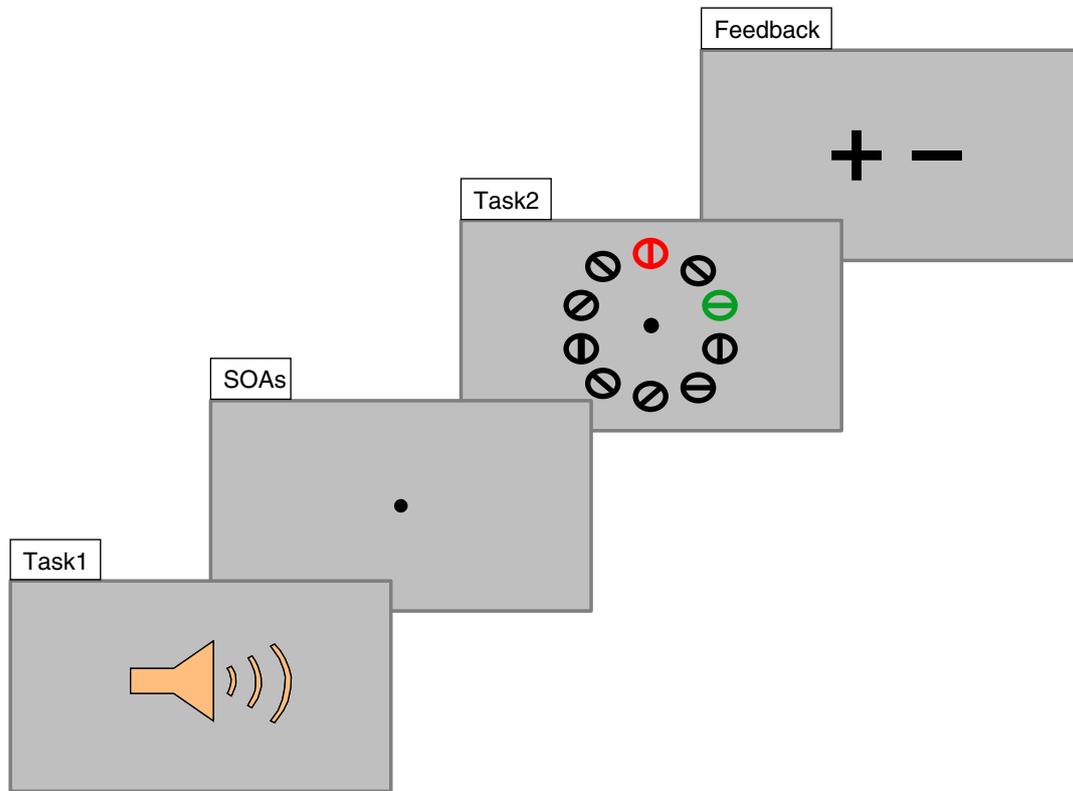


Fig. A.1. Event sequence and example of stimulus displays in the experiment. Each trial began with a pure tone (T_1), followed, after an SOA of 150, 450, or 950 ms, by a visual display containing two colored circles and eight grey circles arrayed on a larger circle centered on fixation (T_2). Task₁ was to report the pitch of the tone and Task₂ was to report the orientation of the line inside the target circle. Accuracy feedback was provided after the second response.

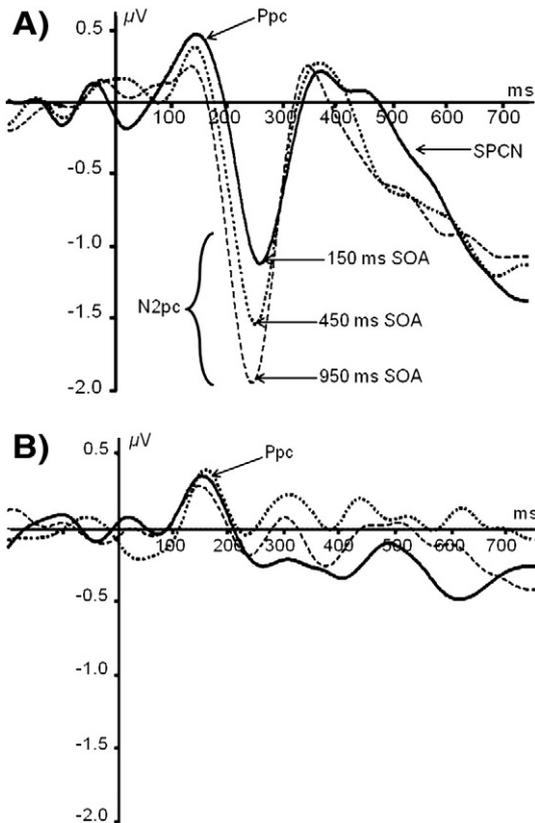


Fig. A.2. Grand average event-related lateralization (ERL) subtraction waveforms (contralateral minus ipsilateral) at PO7–PO8 for each SOA. A) ERLs for the lateral target condition. B) ERLs for the lateral distractor condition.

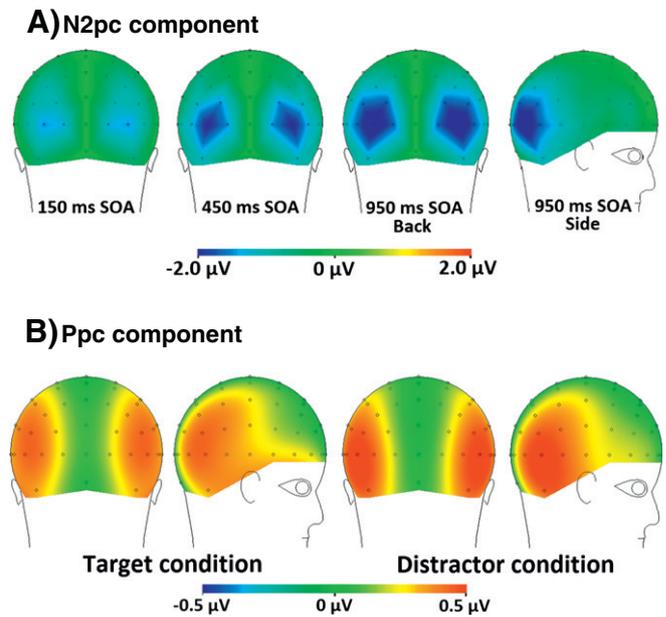


Fig. A.3. Scalp distribution of the mean amplitude of the event-related lateralization (ERL) waveforms. A) N2pc time window (230–260ms) for each SOA in the lateral target condition. B) Ppc time window (130–160ms) for the lateral target condition and the lateral distractor condition.

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