Université de Montréal

Central attention and visual-spatial attention: Electrophysiological investigations of early psychological refractory period multitasking interference

par

Benoit Brisson

Département de psychologie
Faculté des arts et sciences

Thèse présentée à la Faculté des études supérieures
en vue de l'obtention du grade de Philosophiae Doctor (Ph.D.)
en Psychologie option Sciences Cognitives - Neuropsychologie

Août, 2008

Library and Archives
Canada

Published Heritage
Branch

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque et
Archives Canada

Direction du
Patrimoine de l'édition

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 978-0-494-58159-9
Our file Notre référence
ISBN: 978-0-494-58159-9

NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

Université de Montréal
Faculté des études supérieures

Cette thèse intitulée :

Central attention and visual-spatial attention: Electrophysiological investigations of early psychological refractory period multitasking interference

présentée par :
Benoit Brisson

a été évaluée par un jury composé des personnes suivantes :

Martin Arguin, président-rapporteur
Pierre Jolicœur, directeur de recherche
Frédéric Gosselin, membre du jury
Vincent Di Lollo, examinateur externe
Stéphane Molotchnikoff, représentant du doyen de la FES

Abstract

Visual-spatial attention is thought to enhance perceptual processing of attended items in the visual field, both when it is deployed voluntarily, according to the individual's goals, and when it is captured involuntarily by an external stimulus, despite the individual's volition. On the other hand, central attention is thought to select the perceptual representations that will gain preferential access to capacity-limited central processes in multitasking situations. It is still unclear whether these two types of attention are independent or whether they share at least some common mechanisms.

The first goal of the present thesis was to combine the event-related potential (ERP) technique with variants of the psychological refractory period (PRP) dual-task paradigm to investigate the relationship between central attention and visual-spatial attention. The second goal was to examine carefully the time course of interference in the cross-modal PRP paradigm to evaluate if attention-limited central processing in a first auditory task interferes with perceptual processes in a second visual task, such as task-relevant feature detection, visual discrimination, and consolidation into visual short-term memory.

Results reported here clearly demonstrate that central attention interferes with both the voluntary and the involuntary deployment of visual-spatial attention, and that concurrent processing of a tone delays visual short-term memory consolidation and interferes with visual discrimination processes (and maybe more general visual processing) in variants of the PRP paradigm, but does not seem to interfere with pre-attentive task-relevant feature detection.

Keywords : Cognitive neuroscience, dual-task interference, psychological refractory period, central attention, visual-spatial attention, human electrophysiology, event-related potentials, visual P1, occipital N1, N2pc, SPCN

Résumé

L'attention visuospatiale augmente l'efficacité du traitement perceptuel des items auxquels on porte attention, aussi bien lorsqu'elle est déployée volontairement, selon les objectifs de l'individu, que lorsqu'elle est déployée involontairement, indépendamment de la volition. Pour sa part, l'attention centrale sélectionne les représentations perceptuelles qui auront accès aux processus centraux en situation de multitâche. Il reste toujours à savoir si ces deux types d'attention sont indépendants ou si elles partagent certains mécanismes.

Le premier objectif de la présente thèse était d'investiguer, à l'aide du paradigme de la période réfractaire psychologique (PRP) et des potentiels évoqués, la relation entre l'attention centrale et l'attention visuospatiale. Le second objectif était d'investiguer le décours temporel de l'interférence dans les paradigmes de PRP afin d'évaluer si les processus centraux impliqués dans une première tâche auditive interfèrent avec des processus perceptuels impliqués dans une seconde tâche visuelle, tels que la détection des caractéristiques pertinentes à la tâche, la discrimination visuelle, et la consolidation en mémoire visuelle à court-terme.

Les résultats que l'on rapporte ici démontrent clairement que l'attention centrale interfère sur l'attention visuospatial, aussi bien lorsqu'elle est déployée volontairement qu'involontairement, et que le traitement d'une première cible sonore retarde la consolidation en mémoire visuelle à court-terme et interfère sur des processus de discrimination perceptuelle d'une seconde cible visuelle (ainsi que, peut-être, sur des processus plus généraux du traitement visuelle), mais pas sur la détection pré-attentionnelle des caractéristiques pertinentes à la tâche.

Mots-clés : Neuroscience cognitive, interférence en double-tâche, période réfractaire psychologique, attention centrale, attention visuospatiale, électrophysiologie humaine, potentiels évoqués, P1 visuelle, N1 occipitale, N2pc, SPCN

Table of content

List of tables

Article 1: Electrophysiological evidence of central interference in the control of visuospatial attention.

Article 2: A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials.

Article 3: Contingent capture of visual-spatial attention requires central mechanisms: Evidence from event-related potentials and the psychological refractory period.

Article 4: Cross-modal multitasking processing deficits prior to the central bottleneck revealed by event-related potentials.

List of figures

Article 1: Electrophysiological evidence of central interference in the control of visuospatial attention.

Article 2: A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials.

Article 3: Contingent capture of visual-spatial attention requires central mechanisms: Evidence from event-related potentials and the psychological refractory period.

Article 4: Cross-modal multitasking processing deficits prior to the central bottleneck revealed by event-related potentials.

List of abbreviations

AB: attentional blink

EEG: electroencephalogram

ERP: event-related potential

N2pc: N2 posterior contralateral

PRP: psychological refractory period

RSVP: rapid serial visual presentation

RT: reaction time

RT1: reaction time in the first task

RT2: reaction time in the second task

SOA: stimulus onset asynchrony

SPCN: sustained posterior contralateral negativity

T1: first target

T2: second target

Task 1: first task

Task 2: second task

Remerciements

D'abord et avant tout, je tiens à remercier Pierre Jolicœur, mon superviseur. Je ne peux compter le nombre de fois où je me suis trouvé chanceux d'être tombé sur lui! C'est grâce à lui que je peux écrire ces lignes aujourd'hui (littéralement, car il a su me convaincre de rester quand je voulais tout abandonner). Il a été d'une présence importante tout au long de mon parcours des dernières années, de mon premier talk en passant par mon mariage! De plus, il a était d'un soutien inespéré, m'accordant des HEURES à son bureau, de l'encouragement, des idées, des sous et même un bureau portatif pour que je puisse continuer à travailler tout en profitant des premières années de vie de mes enfants. Pierre et le labo ont fait partie de grandes étapes dans ma vie et ont été témoins d'une métamorphose assez spectaculaire, toujours dans la joie, les blagues et la bonne humeur.

J'aimerais aussi remercier Pierre d'avoir bâtit un labo très efficace, non seulement au point de vue de l'équipement, mais aussi du personnel. J'ai eu la chance de travailler avec des gens super intéressants (Nathalie et Manon), plusieurs que je compte désormais parmi mes amis. Billie, Catherine et Émilie qui m'ont conseillé, épaulé, écouté, taquiné et qui ont été une motivation de plus pour me traîner au bureau chaque jour. Je tenais aussi à remercier sincèrement et chaleureusement mon cher collègue Nic, qui a commencé en même temps que moi, quand le labo n'était que nos deux bureaux et des montagnes d'articles à lire. Nicolas a été le cœur du labo pendant mes années de doc, tant comme « lab engineer » (job qu'il déteste, mais a fait de bon cœur!) qu'en tant que « sounding board », toujours un des seuls intéressé par mes idées de recherche (et surtout toujours prêt à les contester!). Sur le plan professionnel, je ne me serais jamais rendu où je suis sans eux.

Par ailleurs, ma vie personnelle fait aussi partie intégrante du labo : j'en ai marié une membre! J'aimerais remercier Alexia, ma merveille conquise, ainsi que Maïka et Mannek, mes merveilles conçues. Ma famille reste, sommes toutes, mon plus bel accomplissement et ma plus grande fierté. Un gros merci aussi à mes beaux-parents, Maryse et Maurice, qui m'ont conseillé, encouragé et dépanné plus d'une fois pendant l'élaboration de ma thèse et surtout à mes parents, qui en ont fait de même et bien plus (je dois compter mon père parmi ces rares intéressés toujours prêts à m'écouter parler de ma recherche !).

Un grand merci aussi à madame Marcelle Cossette-Ricard pour sa grande gentillesse et pour avoir facilité mon passage des études sous-graduées en Biologie aux études graduées en Psychologie.

Enfin, je tiens à remercier la Faculté de Études Supérieures pour m'avoir offert plusieurs bourses dont celle d'accès direct au Ph.D. Je voudrais aussi remercier le Conseil de Recherches en Sciences Naturelles et

Génie et le Fonds Québécois de la Recherche sur la Nature et les Technologies pour les bourses qu'ils m'ont octroyées.

Les montagnes au loin-
reflet dans les prunelles
d'une libellule

Yosa Buson (1717-1783)

General introduction

Overview

Some stages of human information processing have a limited capacity. It is therefore often impossible, at any given time, to process extensively all the information contained in our environment. For this reason, selection of relevant locations and/or relevant stimulus attributes must be performed so that stimuli in these relevant locations and/or stimuli possessing these relevant attributes can benefit from preferential processing. This kind of selection is mediated by our attentional system and, in the visual domain, has been termed visual-spatial attention.

Attention is also implicated in our limitations to perform multiple concurrent tasks. Because central stages of processing have a limited capacity, only a subset of information can proceed, at any given time, through these stages. Limitations in multiple task situations have been linked to what is termed central attention.

Although visual-spatial attention and central attention have been studied extensively, fundamental questions concerning their relationship have just recently started to be investigated empirically. Are visual-spatial attention and central attention independent or do they share common mechanisms? Specifically, is the control of visual-spatial attention dependent on central attention mechanisms? So far, no direct, clear-cut evidence in favour of independence or shared mechanisms have been provided.

The first main objective of the present thesis was to use the event-related potential (ERP) technique in combination with variants of the psychological refractory period (PRP) dual-task paradigm to answer this fundamental question. The second main objective was to take advantage of the ERP technique to investigate directly the time course of multitasking interference in the cross-modal PRP paradigm.

In the following sections, I will describe visual-spatial attention and central attention in relation to the different paradigms that have been used extensively to study each of them. Afterwards, I will present the few studies that have investigated their relationship, starting with those that favour independence and then those that favour shared mechanisms. Finally, before presenting the research hypothesis, I will present briefly the ERP technique, its advantages and limits, and the principal ERP components of interest in the present thesis.

Visual-spatial attention

Two types of paradigms have been widely used in the study of visual-spatial attention: spatial cueing and visual search.

Spatial cueing (and contingent capture)

In typical spatial cueing experiments, trials begin with either an endogenous cue (e.g., a central arrow that points to the to-be-attended location) or an exogenous cue (e.g., a peripheral visual transient at the to-be-attended location), followed by a target, to which a speeded response is often required. The target appears either at the cued location (valid trials) or at another location (invalid trials). Several behavioral studies (e.g., Posner, 1980; Jonides, 1981; Müller & Rabbitt, 1989) have shown that performance is better (shorter reaction times (RTs) sometimes accompanied by more accurate responses) for valid trials relative to invalid trials in both endogenous and exogenous cueing paradigms. These results have been accounted for by postulating that visual-spatial attention is deployed to the location indicated by the cue and when an item appears in this attended location, it benefits from preferential processing.

It is noteworthy that although a validity effect is observed in both endogenous and exogenous cueing tasks, different patterns are found depending on the type of cue. Specifically, the validity effect emerges more rapidly and has a shorter time course for exogenous cues than for endogenous cues. Moreover, with exogenous cues, there is often a validity effect even if the cue is not predictive and therefore irrelevant for the task, which is not the case with endogenous cues (Jonides, 1981; Müller & Rabbitt, 1989). Based on these and other observations, it has been proposed that endogenous cues provoke voluntary shifts of attention whereas exogenous cues capture attention to their location, independently of the individual's volition.

There has been a long and vigorous debate on whether visual-spatial attention operates at an early perceptual stage (e.g., Hawkins, Shafto & Richardson, 1988) or at a latter decision stage (e.g., Shaw, 1984). However, ERP studies[1] using both endogenous cueing (Mangun & Hillyard,

---

[1] See event-related potential (ERP) technique section for an introduction of the ERP technique.

1991; Mangun, 1995) and exogenous cueing (Hopfinger & Mangun, 1998, 2001) have demonstrated that early perceptual ERP components (P1 and/or N1) are enhanced for items that appear in the attended location compared to items that appear in unattended locations. These early attention effects seem to arise in extrastriate visual areas, usually without (or with very little) latency or scalp distribution modulations (Di Russo, Martinez, & Hillyard, 2003), providing strong evidence that visual-spatial attention operates at an early perceptual level in spatial cueing tasks.

It is well known that visual-spatial attention can be deployed voluntarily to specific locations (and/or items) in the visual field, according to the individual's goals, or can be captured by a sufficiently intense and salient stimulus, independently of the individual's volition. An item can also involuntarily capture attention if it matches the individual's top-down attentional control settings, that is to say, if it shares a characteristic that is relevant for attentional selection, even if the item itself is task-irrelevant. For example, if an observer's task is to respond to a red target, the presentation of a concurrent red distractor will often impair performance, but the presentation of a blue or yellow distractor will not (Folk, Leber, & Egeth, 2002; Folk & Remington, 1998; Lamy, Leber, & Egeth, 2004; Leblanc & Jolicœur, 2005). Such contingent capture effects have been observed for color, shape, movement, and sudden onset (Bacon & Egeth, 1994; Folk, Remington, & Wright, 1994). Recent electrophysiological studies (e.g., Eimer, & Kiss, 2008; Leblanc, Prime, & Jolicœur, 2008; Lien, Ruthruff, Goodin, & Remington, 2008) have demonstrated that contingent capture has a visual-spatial locus, that is, irrelevant distractors that share the relevant attentional selection attract visual-spatial attention to its location.

Visual search

In classical visual search paradigms, rapid responses as to the presence or absence of a predefined target embedded in an array containing multiple distractor items is required. The target can appear anywhere in the array. Therefore, in these paradigms, visual-spatial attention must be oriented towards relevant features, and not towards relevant locations, as is the case in spatial cueing paradigms.

While typical spatial cueing experiments compare the performance between valid and invalid trials, typical visual search experiments compare performance across search arrays that vary in the number and type of items that they contain.

Classical behavioral results (Treisman & Gelade, 1980) have shown that RTs were nearly independent of the number of items in the array (shallow search slopes) when the target differed from the distractors in one salient feature (e.g., a blue T amongst brown Ts and green Xs). However, RTs became increasingly slower as the number of items in the array increased (steep search slope) when the target was defined by a conjunction of features (e.g., a green T amongst brown Ts and green Xs).

Treisman and colleges developed the feature integration theory to account for these results. Feature integration theory postulates that there are two stages of processing: 1) a parallel pre-attentive stage followed by 2) a serial attentive stage. The parallel, pre-attentive stage is sufficient to detect salient features. However, when a conjunction of separable features is needed to distinguish the items in the array, visual-spatial attention has to be deployed serially on each individual item so that the item's features can be binded together into a unique percept. The increase in RT as a function of the number of items in the array is therefore assumed by feature integration theory to reflect the time necessary to deploy visual-spatial attention from one item to the next. The question of whether items are attended in serial or in parallel during demanding visual search has created a long-standing debate. However, Woodman and Luck (1999, 2003a) have recently provided strong electrophysiological evidence that visual-spatial attention can rapidly shift from one object to the next in at least some demanding visual search tasks.

The feature integration theory is a feedfoward model, in which the attentive stage has no influence on the pre-attentive stage. This characteristic of feature integration theory has been criticized. Indeed, Wolfe, Cave, and Franzel (1989) have found that when items were presented in high contrast, even conjunction search could produce shallow search slopes. Moreover, they found that search was more efficient (shallower search slopes) when the target differed from the distractors in two dimensions (triple conjunction) than when the target differed from the distractors in only one dimension (simple conjunction). These and other findings, like the distractor similarity effects (Duncan & Humphreys, 1989), led Wolfe and colleagues to propose the guided search model (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994). The main difference between the guided search model and the feature integration theory is that in the guided search model, top-down and bottom-up information is combined in a way that allows the second attentive stage to find the target efficiently. Therefore, contrary to the feature integration theory, which predicts that attention is never implicated in easy visual search tasks where the target differs from the distractor in one salient feature, the guided search model predicts that attention is operative even in these easy search tasks.

Although these two models of visual search differ in the postulated relationship between the pre-attentive stage and the attentive stage, they both postulate two stages of processing, with an initial parallel pre-attentive stage followed by a more demanding serial attentional stage that is required in demanding visual search (searches that provide steep search slopes). Although conjunction searches can induce steep and shallow slopes, depending on the stimuli characteristics (e.g., salience), searching for a randomly oriented target amongst randomly oriented distractors that share the same features but in different spatial configurations (e.g., a randomly oriented L amongst randomly oriented Ts) always produces steep slopes, and therefore unambiguously requires visual-spatial attention.

Early ERP components (P1 and/or N1) are enhanced for task-irrelevant probes that appeared at the target location compared to probes that appeared at a distractor location (e.g., Luck, Fan, & Hillyard, 1993), demonstrating that visual-spatial attention also affects processing at early perceptual stages in at least some demanding visual search tasks.

Central attention

The limits in performing multiple concurrent tasks have been linked to central attention. Two dual-task paradigms have been especially well studied: the psychological refractory period (PRP) and the attentional blink (AB). Each paradigm seems to tax different specific central processing stages, but hybrid dual-task paradigms have shown that attentional mechanisms stressed in PRP and AB paradigms are not independent, and therefore seem to share the same central attention resources.

The psychological refractory period (PRP) paradigm

The PRP paradigm, developed by Telford in the early 1930s (Telford, 1931) and refined by Welford (1952), has been widely used to study attention limitations in dual-task situations. It is a very simple paradigm in that two distinct targets, T1 and T2, are presented sequentially, and a separate speeded response is required for each target. The overlap between T1 and T2 processing (i.e., between Task 1 and Task 2) is typically manipulated by varying the temporal interval between the onsets of the two targets (i.e., the T1-T2 stimulus onset asynchrony, or SOA). Even with very simple stimuli (e.g., pure tones and letters) and associated tasks (e.g., discriminating between a low and a high pitched tone and discriminating between the letters X and O), the PRP paradigm yields robust interference effects, reflected principally by a slowing in mean RT to the second target (RT2) as SOA is reduced (i.e., as task overlap is increased). Whereas mean RTs to the first target (RT1) are relatively unaffected by SOA, the slope of the RT2 by SOA function approaches -1 at the shortest SOAs, meaning that at the shortest SOAs, the slowing of RT2 is proportionate to the decrease in SOA (see Pashler, 1994).

Probably the most influential model of PRP interference has been the central bottleneck model (McCann & Johnston, 1992; Pashler & Johnston, 1989; Pashler, 1994; Welford, 1952). The central bottleneck model postulates that central processes such as response selection and decision making can only operate on one representation at a time. Therefore, under high task overlap conditions, response selection to T2 is postponed until central mechanisms are free from selecting the response to T1. This postponement leads to a longer waiting period as task overlap increases, which would explain the lengthening of RT2 as SOA is decreased in classical PRP paradigms. Importantly, proponents of this type of model also usually assume that, under appropriate conditions (e.g., when sensory modalities are not overloaded and when responses do not require the same output modality), early sensory-perceptual processes that lead to stimulus identification (and response execution processes that lead to the overt response) can operate in both tasks in parallel, without interference, and can proceed simultaneously with the central bottleneck stage(s).

Several aspects of the central bottleneck model have been challenged. For example, it has been proposed by some that the bottleneck is strategic in nature (and so should be eliminated under appropriate conditions; see Meyer & Kieras, 1997), while others have demonstrated that a class of central capacity sharing models (e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2003) are viable alternatives to the central all-or-none bottleneck model. However, the relatively late, central locus of interference in the PRP paradigm is accepted by virtually all researchers and incorporated into most models of dual-task interference.

The locus-of-slack method has been extensively used to determine the locus of interference in the PRP paradigm (McCann & Johnston, 1992; Pashler & Johnston, 1989; Schweickert, 1980). The method is based on a simple principle, which states that if dual-task interference is caused by a processing bottleneck which cannot operate concurrently on more than one target at a time, then a manipulation of the duration of processing in Task 2 will interact differently with SOA depending on whether it occurs before or at/after the bottleneck stage(s). Remember that according to bottleneck models: 1) bottleneck processing in Task 2 has to wait until the bottleneck is released from Task 1, 2) the waiting period lengthens as SOA shortens, and 3) processing before and after the bottleneck can proceed in parallel with the bottleneck stage, without interference. Therefore, at short SOAs, if the difference in duration of processing due to the Task 2 manipulation is before the bottleneck, then it can be absorbed in the waiting period, or "cognitive slack" period, resulting in an underadditive effect. However, if the stage that was affected by the manipulation is at or after the bottleneck, then additive effects of the manipulation and SOA are predicted. That is, the effects of the Task 2 manipulation will be equal at short and long SOAs because the difference in duration of processing due to the Task 2 manipulation takes place after the cognitive slack caused by bottleneck processing in Task 1 and consequently cannot be absorbed into slack.

The locus-of-slack method has provided strong evidence for a late, central bottleneck at the stage of response selection/decision making. Indeed, whereas additive effects have been observed when factors that are argued to influence response selection were manipulated, such as stimulus repetition (Pashler & Johnston, 1989), response compatibility (McCann & Johnston, 1992), and number of response alternatives (Schubert, 1999; Van Selts & Jolicœur, 1997), underadditive effects have been observed when stimulus intensity (Pashler, 1984; Pashler & Johnston, 1989; Oriet & Jolicœur, 2003), stimulus clarity (i.e., intact versus distorted letters; Johnston, McCann, & Remington, 1995) and perceptual degradation (Dell'Acqua, Pascali, & Peressotti, 2000) have been manipulated.

Manipulating the duration of specific processing stages in Task 1 at short SOAs can also inform us on the locus of the PRP effect, in that manipulating the duration of stages at or before the bottleneck in Task 1 is expected to carry over on RT2; that is, it should not only affect RT1, but also RT2 to the same extent. On the other hand, manipulating stage(s) of processing after the bottleneck should not affect RT2. In line with a response selection bottleneck, manipulating response selection demands in Task 1 modulates the PRP effect (Karlin & Kestenbaum, 1968), whereas increasing the duration of response execution has only a minimal effect on RT2 (Pashler & Christian, 1994; but see Ulrich, Fernàndez, Jentzsch, et al, 2006 for evidence of carry over of the difficulty in executing complex movement patterns).

Although response selection is thought to be the major component of the PRP bottleneck, it is worth mentioning that it is not the sole process constituting the central bottleneck. Indeed, carry over or additive effects have been observed when manipulating the duration of stimulus classification (Johnston & McCann, 2006), short-term consolidation (Jolicœur & Dell'Acqua, 1998), mental rotation (Ruthruff, Miller, & Lachman, 1995), and memory retrieval (Carrier & Pashler, 1995).

Several ERP studies have also corroborated the late, central locus of the PRP effect. The first PRP studies using the ERP technique focused on the lateralized readiness potential (LRP), which is thought to index response selection (see Coles, 1989). The LRP is a lateralized ERP component that is maximal over the motor cortex at electrode sites contralateral to the response hand when manual responses are required, and can easily be isolated by creating a difference wave in which the activity recorded at electrodes ipsilateral to the response hand (left electrode for left hand responses and right electrode for right hand responses) is subtracted from the activity recorded at electrodes contralateral to the response hand (right electrode for left hand responses and left electrode for right hand responses).

The LRP can be timelocked to the stimulus onset (stimulus-locked LRP) or to the motor response (response-locked LRP). Given that the LRP reflects response selection processes, the time interval between the stimulus onset and the stimulus-locked LRP onset can be taken as a measure of the duration of processes that occur before response selection, whereas the time interval between the onset of the response-locked LRP and the motor response can be taken as a measure for the duration of motor initiation and execution processes.

Osman and Moore (1993) demonstrated that the latency of the stimulus-locked LRP elicited by Task 2 (T2-locked LRP) was increasingly delayed as SOA decreased, in the same manner as RT2, whereas the interval between the onset of the response-locked LRP elicited in Task 2 (R2-locked LRP) and the second response was unaffected by SOA. Moreover, the T2-locked LRP sometimes preceded the response in Task 1, suggesting that response selection in Task 2 could sometimes be completed prior to response execution in Task 1. Combined, these results suggest that the locus of the PRP effect occurs at or before response selection. Results of a subsequent PRP study which also focused on the LRP (Sommer, Leuthold, & Schubert, 2001) pointed to the same conclusions.

Osman and Moore (1993) provided an upper-bound of processing interference in the PRP paradigm, in that they demonstrated that PRP interference was at or before response selection, as indexed by the LRP. To investigate whether some PRP interference could be observed prior to response selection, Luck (1998) examined the P3 component, which is relatively insensitive to factors that influence response-selection processes, such as stimulus-response compatibility (Magliero, Bashore, Coles, & Donchin, 1984), and is often thought to be an index of updating in short-term memory, or short-term consolidation (Donchin, 1981; but see Verleger, 1988).

In Luck's study, a visual-visual PRP paradigm was used in which both T1 and T2 were presented at fixation, and SOAs were 50 ms, 150 ms, or 350 ms. Capitalizing on the well known fact that the P3 component is larger for infrequent task-defined target categories than for frequent task-defined target categories, Luck (1998) isolated the frequency-related P3 component from other frequency-insensitive activity, including overlapping Task 1 activity, by subtracting the ERP for frequent-T2 category stimuli trials from the ERP for infrequent-T2 category stimulus trials. The amplitude of the T2-locked P3 component was significantly smaller in short SOA trials (50 ms SOA) than in long SOA trials (350 ms SOA). Although the effect on P3 latency was only 51 ms, compared to the 220 ms effect on RT2, it was also significant. However, neither the amplitude nor the latency of the P2 component, which often precedes the P3 in the infrequent minus frequent difference waveform, was significantly modulated by SOA. Because it logically ensues that task defined target category frequency-related components can not be elicited before the task-defined category has been identified, the P2 results in this study suggest that, in agreement with prominent models of dual-task interference, early sensory-perceptual processes that lead to target identification and categorization could operate without significant interference from concurrent processing in the first task, although the modulation of the P3 component may indicate that some interference can occur prior to response selection (e.g., at the level of consolidation in short-term memory).

Recently however, Dell'Acqua, Jolicœur, Vespignani, & Toffanin (2005) observed SOA effects on P2 amplitude and on both P2 and P3 latency in a study that was very similar to Luck (1998), but in which a different range of SOAs was used (SOAs of 100 ms, 350 ms, or 800 ms). Moreover, P3 latency effects were positively correlated with the PRP effect across subjects for whom a clear P3 was elicited. These results were interpreted as evidence in favour of the central interference theory (Jolicœur, 1998, 1999a, 1999b; see section Links between the AB and PRP), which postulates that short-term consolidation (reflected by the P3 component) and response selection (postulated to be the main locus of the PRP effect) share common limited central resources. However, as discussed in Article 4, these results provide a new upper-bound of processing interference and leaves open the possibility that, although response selection seems to be the main locus of interference in the PRP paradigm, it may begin nevertheless to occur before stimulus identification or classification (i.e., at a perceptual level of processing).

The attentional blink (AB)

In typical AB paradigms, two targets are embedded in a rapid serial visual presentation (RSVP) of distracters presented at fixation. Responses are made off-line, at the end of each trial, without speeded pressure. Therefore, contrary to PRP paradigms, were RTs were the main dependant variable, accuracy is usually the main dependant variable in AB paradigms. If participants are instructed to report the identity of both T1 and T2, the accuracy of responses to T2 is often impaired when it is presented within 500 ms of T1, with maximum deficit between 200 and 300 ms (Chun and Potter, 1995; Jolicœur, 1998; Raymond, Shapiro, & Arnell, 1992). Furthermore, when subjects are instructed to ignore T1, they often do not have difficulty in reporting T2. In light of these and other observations, it has been suggested that when attentional mechanisms are engaged in processing T1, they are not available to process a subsequent target (T2) effectively, which leads to the functional "blindness" observed in the AB.

Jolicœur (1998) proposed a central interference model to account for the AB phenomenon. This model proposes that consolidation into short-term memory is time consuming and capacity-limited, and thus acts as a processing bottleneck. In other words, we cannot consolidate T1 and T2 representations at the same time. While T1 representation is being consolidated in short-term memory for further report, T2 representation has to wait, and during the waiting period decays, or is susceptible to be overwritten by a subsequent item in the RSVP.

Vogel, Luck, and Shapiro (1998) provided electrophysiological evidence that supports Jolicœur's central interference model of the AB. Specifically, they found that perceptual components (e.g., P1 and N1) were not modulated during the blink period (see also Sergent, Baillet, & Dehaene, 2005). Perhaps more surprisingly, they found that the N400 component, which reflects semantic mismatch (and therefore requires semantic knowledge of the item being processed to be elicited), was not modulated during the blink period (see also Luck, Vogel, & Shapiro, 1996; Rolke, Heil, Streb, & Hennighausen, 2001). However, the frequency-related P3 component, which has been suggested to reflect consolidation into short-term memory (e.g., Donchin, 1981; Luck, 1998), was completely abolished during the blink period, as would be predicted by the central interference model. Vogel and Luck (2002) have extended the P3 component findings by demonstrating that the frequency-related P3 is abolished in the blink period only when T2 is masked by a subsequent item in the RSVP stream. If T2 is presented at the end of the RSVP stream (and therefore is not masked by a subsequent item), the P3 component is not reduced in amplitude but delayed (Vogel & Luck, 2002). These electrophysiological results are coherent with behavioral studies that found no blink when T2 was presented at the end of the RSVP stream (Giesbrecht & Di Lollo, 1998; Jolicœur, 1999a).

Jolicœur's central interference model predicts that the short-term consolidation stage takes inputs from multiple sensory modalities and that the AB is thus caused by an amodal central bottleneck. Thus, the central interference model would predict that the delay of the P3 component observed by Vogel and Luck (2002) should be observed independently of whether T1 and T2 are presented in the same sensory modality (T1 visual/T2 visual or T1 auditory/T1 auditory) or in different modalities (T1 auditory/T2 visual or T1 visual/T2 auditory), which is exactly what has been observed in recent papers by Arnell and colleagues (Arnell, 2006; Ptito, Arnell, Jolicœur, & MaCleod, 2008).

Links between the AB and PRP

Chun and Potter (1995) have proposed a two-stage model of the AB that is very similar to the central interference model. The sole difference between the two models is that the central interference model predicts an interaction between response selection and short-term consolidation, whereas the two-stage model does not. To test response selection and short-term consolidation interaction, Jolicœur (1999b) varied response selection demands in Task 1 of a typical AB paradigm and in a speeded AB paradigm. The only difference between the speeded AB and AB paradigms is that T1 requires a speeded response in the speeded AB paradigm, while response to T1 is deferred in the typical AB paradigm.

Results showed that T2 accuracy did not depend on the number of Task 1 response alternatives in the typical AB paradigm. Importantly however, T2 accuracy decreased as number of Task 1 response alternatives increased in the speeded AB paradigm. These results support the hypothesis that response selection and short-term consolidation depend on common central mechanisms, as postulated by the central interference model. Convergent evidence was also provided by Ruthruff & Pashler (2001), who investigated response selection and short-term consolidation interactions using hybrid AB/PRP and PRP/AB paradigms.

To provide further evidence that response selection in Task 1 delays short-term consolidation in Task 2, independently of T1 and T2 modality, Dell'Acqua, Jolicœur, and colleagues have conducted an ERP study that focused on the frequency-related P3 component (Dell'Acqua, Jolicœur, Pesciarelli, Job, & Palomba, 2003). In Experiment 1, they replicated the P3 results of Vogel et al. (1998) in a typical AB design. Importantly, in Experiment 2, they also observed an attenuation of the T2-locked P3 at short SOAs when T2 was preceded by an auditory T1 that required a speeded response. This study clearly demonstrated that a speeded response to an auditory T1 (as in the PRP paradigm) and an unspeeded response to a masked visual T1 (as in the AB paradigm) had similar consequences on the P3 component elicited by T2.

Arnell and colleagues (Arnell, Helion, Hurdelbrink, & Pasieka, 2004) have replicated the T2-locked P3 latency delay observed by Vogel and Luck (2002) when an unspeeded response to a masked visual T1 was followed by a speeded response to an unmasked auditory T2 (Experiment 1). They found that the P3 latency delay and RT2 effect were about the same size

(RT2 effect = 142 ms; P3 latency effect = 120 ms) and highly correlated. As mentioned above, a similar correlation between the P3 latency effect and the PRP effect was also observed in a typical PRP experiment for participants that elicited a well-defined frequency-related P3 component (Dell'Acqua et al., 2005). In this last study, the size of the P3 latency effect (100 ms) for participants with a well-defined P3 was only a portion of the size of the PRP effect (198 ms), which is expected from the fact that response selection constitutes an additional source of interference which occurs after the P3. Although a correlation between the P3 latency effect and the PRP effect was not observed in Experiment 2 of Arnell et al. (2004), when T1 was unmasked and required a speeded response (as in the typical PRP paradigm), a significant P3 latency effect was nevertheless observed, as in Luck (1998).

Central attention and visual-spatial attention: are they independent or do they share common mechanisms?

Claims for independence

As mentioned above, using the locus-of-slack method, Johnston et al, (1995) demonstrated an attention restriction after letter identification in the PRP paradigm. In another experiment, using the same method (i.e., the locus-of-slack) and same critical stimuli and task, they demonstrated an attention restriction before the stage of letter identification in a spatial cueing paradigm. The critical task was a two-alternative speeded discrimination as to the identity of a letter (A or H). The letters were presented either normally (easy identification) or distorted (difficult identification). When the critical task was incorporated as the second of a PRP paradigm in which an auditory first task was used to occupy central attention, an underadditive effect of identification difficulty with decreasing SOA was observed, indicating that letter identification occurs before the stage that is delayed by allocating central attention to the first task. In a second experiment, visual-spatial attention was directed in a spatial cueing paradigm by a peripheral cue that preceded the presentation of the critical stimulus. In 80% of trials, the letter appeared at the cued location (valid condition) and in the other 20% of trials the letter appeared at the uncued location (invalid condition). An additive effect of identification difficulty with cue validity provided strong evidence that letter identification occurs at or after the stage that is delayed by an invalid cue. The authors argued that visual-spatial attention and central attention are two distinct types of attention because they operate at different stages of processing. However, they investigated the two types of attention in separate experiments. This aspect of their study makes it difficult to observe possible interactions between visual-spatial attention and central attention and, consequently, to determine whether or not they are truly independent.

Pashler (1991), on the other hand, studied the relationship between visual-spatial attention and central attention by using a modified PRP paradigm where the second non-speeded task required a deployment of visual-spatial attention to T2. The first task was a speeded two-alternative discrimination of the frequency of a tone (T1). The second task was an unspeeded four-alternative discrimination as to the identity of T2, which was embedded in an array of eight letters displayed in two rows of four (all letters were selected at random, without constraint, from the set A, B, C, or D). The visual array containing T2 was subsequently masked by eight Xs displayed in the same positions previously occupied by the letters. Pashler argued that if central processing responsible for the PRP effect interferes with the deployment of visual-spatial attention, then the deployment of visual-spatial attention to T2 would be postponed until central mechanisms are free from selecting the response to T1. Because T2 was masked, there was a critical time period for visual-spatial attention to be deployed to T2 before the mask terminated sensory-perceptual processing of the items in the visual display. Following this logic, reducing SOA should result in poorer report of T2 if both types of attention share at least some mechanisms (because of the increased postponement of the deployment of visual-spatial attention as SOA was reduced), whereas no SOA effect on report accuracy for T2 should be observed if the two types of attention are independent. Results showed a significant reduction in T2 accuracy between the shortest (50 ms) and longest (650 ms) SOA when color was used as the selection index (Experiment 7: 4.7%; $p < .005$) and when attention had to be deployed on the opposite side of a peripheral onset cue (Experiment 6: 5.1%; $p < .001$). However, because these SOA effects on T2 accuracy were much smaller than a 30% effect found when the peripheral onset cue itself was delayed (Experiment 2), Pashler concluded that the observed SOA effect on T2 accuracy could not be caused by a lengthy period of central postponement of the deployment of visual-spatial attention. Pashler explicitly acknowledged, however, that he could not, with the behavioral methods used in his study, offer an alternative explanation of the observed significant SOA effects on accuracy in the second task. Moreover, comparing dual-task interference in a PRP paradigm with a delay of the presentation of the probe in a simple task situation is only valid in the context of all-or-none bottleneck models. Indeed, capacity sharing models would predict that even if visual-spatial attention depends on central attention, the deployment of visual-spatial attention to T2 could be accomplished (although less efficiently) while central mechanisms are occupied on the first task if central demands in the first task are not too high (and therefore does not require all central attention resources). Because the first task was only a two-alternative choice discrimination, it is reasonable to presume that response selection was relatively easy, and therefore some central resources were probably still available to control the deployment of visual-spatial attention (although less efficiently) when central attention was occupied in selecting the first response, which would explain the relatively small effect in this study (see Dell'Acqua & Jolicœur, 2000).

Claims for shared mechanisms

Contingent capture studies suggest that visual-spatial attention and later central attention mechanisms may interact. Folk, Leber, and Egeth (2002) have demonstrated that when participants are instructed to detect a uniquely colored item (e.g., red) embedded in a rapid visual serial presentation (RSVP) stream presented at fixation, they are significantly distracted (attentional capture) by a peripheral distractor of the same color (e.g., red), but not by a distractor of different color (e.g., green). These results suggest that attentional control settings can exert a top-down influence on the degree to which bottom-up signals can capture visual-spatial attention. In the same line of thought, Downing (2000) has demonstrated that items that are actively maintained in working memory can involuntarily capture visual-spatial attention.

Other studies have shown an increase of perceptual interference of distractor stimuli on target processing when central attention load is increased (de Fockert, Rees, Frith, & Lavie, 2001; Lavie, Hirst, de Fockert, & Viding, 2004; Jiang & Chun, 2001). According to the authors, these results suggest that visual-spatial attention is impaired when central attention is engaged on a concurrent task. There are no means, however, with behavioral data, to pinpoint directly the exact stage of processing that is impaired when central attention load is increased, and therefore the alternative hypothesis of the loss of control at other stages of processing (e.g., response selection) could not be excluded to explain these results. As mentioned in the following section, in contrast to behavioral measures, ERP waveforms provide continuous millisecond-by-millisecond measures that can be used to observe more directly neural activity that is interposed between the stimulus and the overt response. ERP measures are therefore ideally suited to study the relationship between visual-spatial attention and central attention.

The event-related potential (ERP) technique

ERPs are sequences of positive and negative voltage deflections (referred to as peaks or components) extracted from non-invasive, online electroencephalogram (EEG) recordings using electrodes on the scalp of human participants, often while they perform cognitive tasks. To extract ERP waveforms from the EEG recordings, EEG segments are timelocked to experimental events, most often to the onset of the stimulus, and averaged. This averaging method cancels out random EEG activity and therefore mainly conserves the event-related neural response (ERP waveform).

ERP components are typically named according to their polarity and either their order of appearance (e.g., 'P3' is the third major positive component) or latency (e.g. 'N170' for a negative peak at 170 ms post-stimulus onset). The ERP waveform is thought to represent the flow of information from perception to action, the earliest components reflecting early perceptual processes (e.g., P1/N1) and the latter components reflecting central (e.g., P3) and response-related (e.g., LRP) processes. Given that the P1 and N1 are modality specific, the P1 and N1 elicited by a visual event are completely unrelated to the P1 and N1 elicited by an auditory event, meaning that the visual P1 and N1 have different time courses and scalp distributions than the auditory P1 and N1. Contrary to the early P1 and N1 components, the P3 and later components are largely amodal (e.g., independent of the stimulus sensory modality).

Advantages

First and foremost, the ERP technique not only provides an excellent temporal resolution, in the order of the millisecond, but also provides a continuous measure of processing from stimulus onset to the overt response (and beyond). Whereas behavioral measures (e.g., RT, accuracy) reflect the sum of all processing between the stimulus and the response, the amplitude and latency of ERP components provide direct measures of distinct covert perceptual, cognitive, and response-related processing. Thus, while behavioral measures can only provide indirect evidence as to how processing between the stimulus and the response is affected by an experimental manipulation, ERPs can be used to associate the behavioral effect directly to an effect on a distinct stage of processing (see following section: ERP components of interest in the present thesis).

Second, although ERPs do not provide a very good spatial resolution compared to other neuroimaging techniques, such as functional magnetic resonance imaging (fMRI), scalp distributions of the electric potentials nevertheless provide some spatial information as to the origin of an effect in the brain. Although coarse, this information can be valuable in identifying the stage of processing that is affected by an experimental manipulation. For example, if the ERP waveform elicited by a visual T2 is more negative in the visual N1 time-range under high concurrent dual-task demand, it could be tempting to conclude that Task 1 interfered with perceptual processing in Task 2, as indexed by the visual N1. However, this conclusion would be valid only if the scalp distribution of the visual N1 dual-task effect had the same occipital distribution as the visual N1 component itself. Indeed, an effect in the visual N1 time range could reflect an attenuation of the visual N1 ***per se***, or could reflect overlapping activity that originated in other regions of the brain, such as the prefrontal cortex (which would be hard to reconcile with a perceptual interference account). Demonstrating that an auditory T1 interferes with processing of a visual T2 in the N1 time-range, and that the effect occurs over occipital (visual) cortex would provide a powerful combination of evidence in favour of interference on perceptual processing in a cross-modal dual-task paradigm.

Finally, ERPs can be recorded in absence of an overt response, making them ideal for measuring processing of unattended stimuli or stimuli that failed to be consciously detected (see Hillyard & Picton, 1987). Although this advantage is not of direct concern when investigating dual-task interference in the PRP paradigm, where accuracy usually approaches ceiling and is typically unaffected by task overlap (at least when T2 is not masked), it can become a major advantage in other dual-task paradigms, such as the AB (Chun & Potter, 1995; Jolicœur, 1998;

Raymond et al., 1992), for which dual-task interference is reflected by a drop in accuracy.

Limitations

First, as mentioned above, ERP waveforms are computed by averaging EEG segments, often of up to hundreds (or sometimes even thousands) of trials. It is therefore often impractical to obtain trial-by-trial measures. Furthermore, the success of this averaging procedure relies on the constancy of trial-by-trial processing. Any variation in processing can result in the attenuation, smearing, or even the loss of an associated ERP component. It is therefore important to control timing variations in processing, especially when studying cognitive components with a small amplitude. The large number of trials that are often required to obtain a reliable ERP waveform also limits the number of conditions that can be included in an experimental design using this technique, limiting the range of questions that can be investigated with ERPs.

Also, ERP waveforms are very complex and consist of the sum of numerous components that can overlap in time. Furthermore, a component, such as the visual N1, can reflect the sum of multiple sub-components, each reflecting a particular process. It can therefore be hard (but not impossible) to determine which ERP component, or sub-component, is affected by an experimental manipulation. For example, an increased negativity in the visual N1 time range could reflect an increase in visual discrimination processing, task-relevant feature detection, or the addition of another unrelated overlapping component. As mentioned above, scalp distributions, for example, can be useful to distinguish between these possibilities.

Isolation of T2 related ERPs from overlapping activity in dual-task studies

When two targets are presented in close temporal succession, as in dual-task studies, the ERPs associated to T1 processing (e.g., Task 1) will overlap with the ERPs associated to T2 processing (e.g., Task 2). Disentangling the ERP waveform elicited by each task (and from the intervening distractors, if any) can be particularly challenging. Fortunately, under most conditions, voltage fields summate linearly (Luck, 2005) enabling the use of subtraction methods to compute difference waves that reflect specific T2 processes uncontaminated by overlapping activity.

For example, it is well-known that the N400 component is sensitive to the degree of semantic mismatch between a word and a previous context (Kutas & Hillyard, 1980). The word "bird," for instance, would elicit a large N400 if preceded by the context word "apple" but not if it was preceded by the word "feather." It is therefore possible to vary the degree of semantic mismatch between a context word and T2, and create N400 difference waves under conditions of high and low dual-task interference to isolate the N400 (see Luck et al., 1996, Rolke et al., 2001; Vogel et al, 1998). As detailed above, difference waves have also been used extensively in dual-task studies to isolate other components, such as the LRP (e.g., Osman & Moore, 1993; Sommer, Leuthold, & Schubert, 2001) and P3 (Arnell et al., 2004; Dell'Acqua et al., 2003, 2005; Luck, 1998; Ptito et al., 2008; Vogel et al., 1998; Vogel & Luck, 2002). In the present studies, we focused on other ERP components that can also be isolated using difference waves, such as the N2pc, an index of visual-spatial attention, and the sustained posterior contralateral negativity (SPCN), an index of visual short-term memory. In the fourth study, we also developed a subtraction method to isolate the ERP waveform associated to T2 processing from overlapping T1 activity, enabling uncontaminated measurements of the visual P1 and N1 elicited by T2 (for another example of the successful use of a similar subtraction methods, see Luck, Fan, & Hillyard, 1993).

ERP components of interest in the present thesis

N2pc component

The N2pc is though to index visual-spatial attention. It is maximal at occipital lateral electrode sites (e.g., PO7/PO8) contralateral to a target (or any other voluntarily or involuntarily attended item: see Hickey, McDonald, & Theeuwes, 2006; Kiss, Jolicœur, Dell'Acqua, & Eimer, 2008, Leblanc, Prime, & Jolicœur, 2008; Woodman & Luck, 2003a). In typical N2pc experiments, the target is presented randomly to the left or right of fixation. Low-level sensory activity is equated across visual hemifields (all items in the search display are equated for luminance [small residual differences are controlled by counterbalancing target and distractor colors between subjects]), and the side of the motor response is unrelated to the side of presentation of the target. It is therefore possible to isolate the N2pc from sensory and motor activity by subtracting activity at electrode sites ipsilateral to the attended item from the corresponding activity at electrode sites contralateral to the attended item (e.g., PO7/PO8). Although the N2pc onset latency could vary with the difficulty of target localization (Brisson, Robitaille, & Jolicœur, 2007; Wascher, 2005), and the duration can vary with various aspects of stimulus processing (Leblanc et al., 2008; Robitaille & Jolicœur, 2006), it typically starts about 180 ms post-target onset and lasts about 100 ms.

The N2pc has been linked to the focusing of visual-spatial attention in light of several results. First, the N2pc is absent for nontarget items that could be rejected based on salient, pre-attentive feature information, but is present for both target and nontarget stimuli that require careful scrutiny to be distinguished from the target (Luck & Hillyard, 1994a, 1994b). Second, the N2pc is larger for targets that are defined by a conjunction of features than for targets that are defined by a simple feature (Luck, Girelli, McDermott, & Ford, 1997), which corresponds to the greater attentional demands of conjunction targets (Treisman and Gelade, 1980). Third, the N2pc, which is relatively insensitive to the strength of the bottom-up input (Brisson & Jolicœur, 2007; Brisson, Robitaille, & Jolicœur, 2007), is nevertheless attenuated when the number of nearby distractors is reduced (Luck et al. 1997), which corresponds to the greater attentional demands when nearby distractors are present (Cohen & Ivry, 1991).

Luck and colleagues, who were the first to study this component meticulously in visual search tasks, suggested that the N2pc reflects distractor suppression processes, since the N2pc is eliminated when no distractors are present (Luck & Hillyard, 1994a) or when all the items in the search array are identical (Luck & Hillyard, 1994b). They also argued that another piece of supporting evidence comes from the fact that the N2pc is eliminated when the task requires attending to both target and distractors, as when the target is defined as the one item that differs from the others in the search array (Luck & Hillyard, 1994b). However, all of the evidence mentioned above is also coherent with the hypothesis that the N2pc reflects target enhancement processes. Others who have used bilateral displays with only one distractor (e.g., Eimer, 1996) have put forward this hypothesis.

Although there is still an ongoing debate on the specific processes that underlie the N2pc, it is widely accepted that it is a valid index of the focus of visual-spatial attention, and has been used successfully as a tool to investigate, for example, serial deployment of attention in visual search (Woodman & Luck, 2003a), attentional capture (Eimer & Kiss, 2008; Hickey et al., 2006; Kiss et al., 2008; Leblanc et al., 2008; Lien, Ruthruff, Gooding, & Remington, 2008), change detection (Eimer,& Mazza, 2005; Schankin & Wascher, 2007), inhibition of return (McDonald, Hickey, Green, & Whitman, 2008), multiple object tracking (Drew & Vogel, 2008), the interdependence of spatial attention and lexical access (Dell'Acqua, Pesciarelli, Jolicœur, Eimer, & Peressotti, 2007), links between attention and emotion (Kiss, Goolsby, Raymond, Shapiro, Silvert, Nobre, Fragopanagos, Taylor, & Eimer, 2007), dissociations of visual-spatial allocation and awareness (Woodman & Luck, 2003b), the allocation of visual-spatial attention in unconscious identification (Jaśkowski, van der Lubbe, Schlotterbeck, & Verlegger, 2002), possible impairments of the allocation of visual-spatial attention with advancing age (Lorenzo-López, Amenedo, & Cadaveira, 2008), the speed of visual-spatial attention in schizophrenia (Luck, Fuller, Braun, Robinson, Summerfelt, & Gold, 2006) and possible long term attentional deficits in multiple concussed athletes (De Beaumont, Brisson, Lassonde, & Jolicœur, 2007).

Sustained posterior contralateral negativity (SPCN) component

As the N2pc, the SPCN, which starts at around 300 ms post-target display, is thought to index visual activity, because it arises at electrode sites contralateral to the task-relevant visual items, and has a posterior scalp distribution, which is consistent with activity in the extrastriate visual cortex (McCollough, Machizawa, & Vogel, 2007). Specifically, the SPCN is thought to reflect visual short-term memory activity (Jolicœur, Brisson, & Robitaille, 2008; Klaver, Talsma, Wijers, et al., 1999; McCollough, Machizawa, & Vogel, 2007; Perron, Lefebvre, Robitaille, Brisson, Gosselin, Arguin, & Jolicœur, 2008; Predovan, Prime, Arguin, Gosselin, Dell'Acqua, & Jolicœur, 2008; Vogel & Machizawa, 2004). Indeed, it has been shown that the amplitude of the SPCN increases as the number of to-be-remembered items in the visual display increases, but only up to the participants' visual short-term memory capacity, and that it is a sustained response throughout the retention period (McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004). The increase of SPCN amplitude as the number of to-be-remembered items in the visual display increases has also been reported in choice tasks that were not memory tasks ***per se*** (e.g., Jolicœur et al., 2008). Jolicœur et al. (2008) observed a modulation of the SPCN amplitude by memory load that was not accompanied by a modulation of the N2pc, suggesting that the N2pc and SPCN are indeed two functionally distinct components (a complimentary dissociation is provided in Article 2 of the present thesis).

Visual P1 component

The visual P1 component is maximal over the visual cortex, at lateral occipital sites (e.g., PO7/PO8), and peaks between 100-130 ms after a visual stimulus onset. The visual P1 is considered as an exogenous component because it is always elicited in the presence of a visual stimulus, and its amplitude and latency vary substantially with presentation parameters, such as stimulus contrast and intensity, but are relatively independent from most top-down variables, although it is sensitive to the prior focus of visual-spatial attention (for a review see Mangun, 1995) and the participants state of arousal (Vogel, & Luck, 2000).

Occipital N1 component

The occipital N1 is also maximal over visual cortex, at lateral occipital sites (PO7/PO8), and typically peaks around 150-200 ms after the stimulus onset. As the visual P1, the occipital N1 component is invariably elicited by visual stimuli, and as such is considered as partially exogenous. It is also modulated by visual-spatial attention (for a review see Mangun, 1995). Interestingly, unlike the visual P1, the occipital N1 is larger in discrimination tasks than in detection tasks (the N1 discrimination effect), which has lead some authors to postulate that part of the occipital N1 reflects visual discrimination processes (Vogel & Luck, 2000; Ritter, Simson, Vaughan, & Friedman, 1979). Pre-attentive relevant-feature detection processes are also thought to be reflected by a greater negativity in the occipital N1 time range (i.e., about 140-190 ms post-visual display: Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004).

Research goals and hypothesis

First study

The main goal of the first study was to investigate directly whether concurrent central processing interfered with the voluntary deployment of visual-spatial attention. This was done by measuring the N2pc component elicited by a lateralized visual T2 under different concurrent central load conditions, manipulated using a modified PRP paradigm similar to that used by Pashler (1991).

Three possible results could be encountered. First, the mean N2pc amplitude could be attenuated in the high-load conditions compared with the low-load conditions. This result would suggest that there is less available capacity to deploy visual-spatial attention when central attention is needed to perform Task 1 concurrently, or that on a portion of high-load trials, visual-spatial attention would have been deployed to a distractor item opposite the target or not at all, while on other trials, it would have been deployed without interference to the target location. Second, the N2pc could be delayed in the high-load condition compared to the low-load condition. This result would indicate that the deployment of visual-spatial attention had to wait until attention limited central processing was free from performing Task 1. Third, there could have been no N2pc modulation between the central load conditions. While the two first possible results are consistent with the hypothesis that central attention interferes with visual-spatial attention, the third result would support the hypothesis that the two types of attention are independent and can be performed concurrently, without interference.

Second study

The second study was conditional on the findings of a modulation of the N2pc by central load in the first study, which was observed. The second study was very similar to the first, but was designed to minimize the possibility of differential task preparation between central load conditions. The first goal of this study was to evaluate whether the N2pc findings reported in the first study could be replicated in conditions where differential task preparation between central load conditions was minimized. The second goal was to investigate whether concurrent central processing of the auditory Task 1 interfered with the transfer into visual short-term memory of the visual T2, as indexed by the SPCN.

If the N2pc attenuation observed in the first study were caused by central postponement or capacity sharing responsible for the PRP, then we would expect a progressive attenuation of the N2pc as SOA is reduced, and the attenuation should be significant between the two shortest SOAs. The absence of an effect of SOA on the amplitude of the N2pc would favour the task preparation account.

As for the SPCN, three possible results could be encountered. First, the SPCN amplitude could be progressively attenuated as SOA was reduced. This result would indicate that when central attention is needed to perform Task 1 concurrently, less capacity is available to encode or maintain information in visual short-term memory. Second, the SPCN could be progressively delayed as SOA was reduced. This result would indicate that transfer into visual-short term memory had to wait until attention limited central processing was free from performing the first task. Third, there could be no SPCN modulations between the SOA conditions. While the two first possible results are consistent with the hypothesis that central attention interferes with visual-short term memory processes, as suggested by Dell'Acqua and Jolicœur (2000), the third result would support the hypothesis that visual short-term memory processes could operate concurrently, without interference from attention-limited central processing responsible for the PRP effect, as suggested by Pashler (1993).

Third study

The goal of the third study was to determine whether the involuntary deployment of visual-spatial attention, occurring during the contingent capture of attention, also requires capacity-limited central resources. To accomplish this goal, we used a similar logic as in the two first studies, but we changed Task 2 to a contingent capture task, and the N2pc elicited by the lateralized distractor that matched the observers' top-down attentional control settings (see Leblanc et al., 2008) was measured in different concurrent central load conditions, manipulated with SOA.

If contingent capture of visual-spatial attention does not depend on limited central attentional resources, as would be intuitively expected considering the involuntary nature of attentional capture, the N2pc should be identical in all SOA conditions. On the other hand, if contingent capture of visual-spatial attention does depend on limited central attentional resources, despite its involuntary nature, then the N2pc should be attenuated at short SOAs (i.e., in high concurrent central load conditions).

Fourth study

The primary goal of the fourth study was to investigate whether early visual P1 and N1 sensory-perceptual components elicited by a visual

T2 were modulated by an auditory Task 1 in a variant of the PRP paradigm. We also wanted to replicate the N2pc and SPCN effects observed in the first two studies.

We used the same speeded four-alternative discrimination (4-AD) first task as in the previous experiments. However, here we took advantage of a built-in manipulation of first task difficulty. Indeed, it has been demonstrated that when four tone frequencies arrayed from low to high are mapped to four response keys arrayed from left to right, the mean response times to the highest and lowest frequencies are shorter then those of the middle frequencies, and that this difficulty effect, when manipulated in the first task, delays the onset of processing in the second task (carry over effect; see Jolicœur, 1999a; Jolicœur, Dell'Acqua, & Crebolder, 2000; Van Selst & Johnston, 1996). The T1-T2 SOA was adjusted dynamically so that T2 would be presented usually after the response to T1 when the tone had the lowest or highest frequency (easy-Task 1 condition), but before the response to T1 when the tone had one of the middle frequencies (hard-Task 1 condition). This enabled us to vary task overlap randomly while using identical SOAs in both first task conditions.

To remove overlapping first task activity from the T2-locked ERP waveform of interest, we included single-Task 1 trials in which only T1 was presented. These single-Task 1 trials, randomly intermixed with dual-task trials, were identical to the dual-task trials, except that T2 was not presented and therefore no associated Task 2 was required. By computing the average EEG activity time-locked to T1 onset + SOA (the time at which

T2 would have been presented) in these trials, it was possible to estimate overlapping Task 1 activity, which we then subtracted from the T2-locked (i.e., T1 onset + SOA) dual-task ERPs, thus isolating the ERP associated with T2 processing. Arguments supporting the validity of this subtraction method are presented in Article 4.

In the central bottleneck framework, if concurrent processing of the tone interferes with sensory processing reflected by the visual P1 component, interference should be reflected by latency effects. However, top-down factors, such as visual-spatial attention effects observed in spatial cueing paradigms (see Mangun 1995 for a review) or arousal effects (Vogel & Luck, 2000), are known to modulate the visual P1 amplitude. Therefore, we predict that, if concurrent processing of the tone interferes with the P1, it will be reflected by amplitude effects. It is possible that the P1 arousal effect is caused by top-down inputs in the visual cortex similar to the sensory gain control processes thought to be reflected in the P1 attention effect (Hillyard, Luck, Vogel, 1998). If concurrent processing interferes with the processes underlying the P1 arousal effect, then we could expect to find an effect of Task 1 difficulty on P1 amplitude when T2 is associated to a harder discrimination task, but not if it is associated to an easier detection task.

As mentioned above, the occipital N1 has been found to be larger in discrimination tasks than in detection task, leading some authors to suggest that part of the occipital N1 reflects visual discrimination processing (Ritter, Simson, Vaughan, Friedman, 1979; Vogel & Luck, 2000).

If we observe an attenuation of the occipital N1 in high overlap conditions when T2 is associated to a discrimination task, it will be important to investigate whether we observe the same effect when T2 is associated to a detection task. If a modulation of the amplitude of the occipital N1 is observed only when T2 is associated to a discrimination task, but not if it is associated to a detection task, than we could postulate that the auditory Task 1 interfered specifically with visual discrimination processes.

Pre-attentive relevant-feature detection processes that precede the spatial allocation of attention on the target are also thought to be reflected by a greater negativity in the occipital N1 time range (i.e., about 140-190 ms post-visual display: Hopf et al., 2004). This detection process will be reflected by a greater negativity contralateral to the target (only item in the display that is in the relevant color). It will be possible, when T2 requires a discrimination, to evaluate whether concurrent processing of the tone interferes with this process by looking at the laterality (contralateral vs. ipsilateral) by Task 1-difficulty (easy-Task 1 vs. hard Task 1) interaction, especially in the early portion of the occipital N1 (before the onset of the N2pc). The presence of an interaction could indicate that the auditory Task 1 interfered with pre-attentive feature detection, whereas the absence of an interaction would indicate the absence of interference, as would be expected based on previous results (see Article 1, control experiment).

Articles

Article #1: Electrophysiological evidence of central interference in the control of visuospatial attention

Electrophysiological evidence of central interference in the control of visuospatial attention

Benoit Brisson and Pierre Jolicœur

Centre de recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Qc

Article published in *Psychonomic Bulletin & Review* (2007), 14: 126–132.

Abstract

Visuospatial attention can be deployed to different locations in space without moving the eyes. A large body of human electrophysiological studies reveal enhanced sensory-perceptual responses for stimuli that appear at an attended location. However, it is not clear if the mechanisms that underlie visuospatial attention are under the control of attention mechanisms that limit central processing in multiple-task situations. We investigated this question by incorporating a visual task that required the deployment of visuospatial attention as the second task of psychological refractory period (PRP) dual-task paradigms. The N2pc component of the event-related potential was used as an electrophysiological index of the moment-by-moment deployment of visuospatial attention to monitor when and where observers were attending while they performed concurrent central processing known to cause the PRP effect. Electrophysiological evidence shows that central processing interfered with the N2pc, suggesting that visuospatial attention is under the control of capacity-limited central mechanisms.

Introduction

Visuospatial attention is known to improve performance when stimuli are presented at attended locations (Posner, 1980), and is also thought to be necessary to identify a pre-defined target in a search array, at least when performing difficult search tasks (Treisman & Gelade, 1980). Several electrophysiological studies (see Mangun, 1995, for a review) strongly suggest that early sensory-perceptual processing of attended stimuli is facilitated.

On the other hand, in multiple-task situations, central attention selects information to be processed in capacity-limited central stages. The psychological refractory period (PRP) paradigm has been used extensively to study central attention. In the PRP paradigm, two distinct targets, T_1 and T_2, often presented in different sensory modalities, are separated by various stimulus onset asynchronies (SOA), and a speeded response is required for each target. PRP interference effects are reflected by an increase in mean response time to the second target (RT_2) as the SOA is reduced (Pashler, & Johnston, 1989; Pashler, 1994). Manipulating response selection demands of T_1 modulate the PRP effect (Karlin & Kestenbaum, 1968), suggesting that response selection requires limited central attention mechanisms (Pashler & Johnston, 1989; Pashler, 1994).

Although a large body of evidence shows that visuospatial attention enhances early sensory-perceptual stages of processing and central attention selects information to be processed at later limited central stages, the relationship between these two types of attention is still unclear. Some researchers have claimed that visuospatial attention and central attention are independent (e.g., Jonhston, McCann, & Remington, 1995; Pashler, 1991), whereas others have claimed that they share common mechanisms (e.g., Jiang & Chun, 2001).

Johnston, McCann, and Remington (1995) have cleverly used the locus-of-slack logic to argue that visuospatial attention and central attention operate at different stages of processing. They have nevertheless investigated these two types of attention independently, in two separate experiments. This aspect of their study makes it difficult to observe possible interactions between visuospatial attention and central attention, and consequently to determine whether or not they are independent. Furthermore, the opposite conclusions of Pashler (1991) and Jiang and Chun (2001) suggest that further work on the issue is warranted.

To bring new evidence to bear on this issue, we recorded event-related potentials (ERPs) in addition to behavioral measures. ERP components provide indexes of distinct covert stages of processing that occur between stimulus presentation and the overt response. The ERP component of interest in this study is called N2pc (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 2003). The N2pc — a greater negativity at posterior electrode sites contralateral to the position of an attended visual target — typically occurs about 180-280 ms after the target onset and likely indexes covert visuospatial attention in light of several results reviewed by Woodman and Luck (2003). We measured the N2pc elicited by a lateralized visual target under different concurrent central load conditions manipulated using a modified PRP paradigm similar to that used by Pashler (1991).

If the control of visuospatial attention requires mechanisms or resources that overlap with those that control attention-limited central mechanisms, the interference of central attention (required for Task_1) on visuospatial attention (required for Task_2) should be reflected by an increase in N2pc latency and/or by a reduction in N2pc amplitude in a high-load condition relative to a low-load condition.

Experiment 1

In this experiment, T_1 was a tone and T_2 – which was embedded in a symmetric bilateral visual display – was a uniquely colored square with a gap in one side (see Figure 1). The participants were required to make two speeded button-press responses on each trial, the first to indicate the pitch of T_1 (200, 430, 926, or 2000 Hz) and the second to indicate the location of the gap in T_2 (up, down, left, or right). Overlap between central processing of T_1 and deployment of visuospatial attention on T_2 was manipulated by varying the T_1- T_2 SOA. In the short-SOA condition, attention-limited central processing should still be engaged on T_1 when visuospatial attention must be deployed on T_2. In contrast, in the long-SOA condition, the response to T_1 has usually been made when T_2 is presented, and so capacity-limited central mechanisms should not be busy with T_1, which provides a low-load control condition approximating single-task performance.

Method

Eleven neurologically normal subjects participated in this experiment for financial compensation. Three were excluded from the analyses (see below). Therefore, 8 subjects remained in the sample.

Each subject performed one practice block of 64 trials followed by 8 experimental blocks of 96 trials. The trial sequence is presented in Figure 1. Each trial was initiated by pressing the "N" and "V" keys simultaneously with the right and left index fingers respectively. A fixation point appeared at the center of the computer screen, which was visible throughout the remainder of the trial. Five hundred milliseconds later, a 100 ms tone (T_1) was emitted by two speakers placed on each side of the computer screen. The tone was followed, at an SOA of 100 (short-SOA) or 1500 ms (long-SOA), by a 133 ms bilateral visual display that contained T_2, which in turn was immediately followed by a 100 ms bilateral mask. The visual display contained four colored squares (two on each side of fixation) with a gap in one side (different for each square) and the mask display consisted of four grey squares with a gap in all sides (see Figure 1). All squares in the visual display and mask display subtended a visual angle of 1° X 1° and the gaps were 0.33°. The centre of the squares nearest to fixation was 1.5° below and 3.5° to the left or right of fixation. The centre of the far squares was 3° below and 5° to the left or right of fixation. T_2 appeared randomly on the left or right of fixation and was red amongst green distractors for half of the subjects and green amongst red distractors for the other half. Both colors were approximately equiluminant to equate their low-level sensory response. Responses to T_1 were made with fingers of the right hand (response keys where "N," "M," ",," and "." for the 200, 430, 926, and 2000 Hz tones respectively) and responses to T_2 were made with the fingers of the left hand (response keys were "Z," "X," "C," and "V" for left, bottom, up, and right gaps respectively).

========== Insert Figure 1 about here ==========

The electroencephalogram (EEG) was recorded from 64 active Ag/AgCl electrodes (BioSemi ActiveTwo system) mounted on an elastic cap and referenced to the average of the left and right mastoids. Electrodes were placed according to the extended International 10/10 system. 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. A bandpass filter of 0.01-67 Hz was applied and the EEG and EOG signals, digitized at 256 Hz, were averaged offline.

Trials with artefacts at electrode sites of interest (O1, O2, PO7, PO8, P7, and/or P8 electrode sites), eye blinks (VEOG > 100 μV) and large horizontal eye movements (HEOG > 35 μV) were excluded from the analysis.

Using the procedure described in Woodman and Luck (2003), one subject with residual eye movements that deviated more then 0.2° (i.e., HEOG > 3.2 μV) towards the target after ocular artefact rejection was rejected from the analysis. Because we were investigating N2pc modulations, we rejected one subject that did not elicit an N2pc in either condition (N2pc mean amplitude of less than -0.3 μV at PO7/PO8 sites in both conditions)[1]. One more subject was rejected because T_2 accuracy was at chance.

Results and discussion

Behavioral results are presented in Table 1. Only trials with correct responses to both T_1 and T_2 were included in the RT analyses, and outliers were excluded using the method described in Jolicœur (1999b). Repeated measures ANOVAs with SOA conditions (short vs. long) as a factor revealed that T_1 accuracy was not affected by SOA ($F(1,7) = 1.1$, $p > .33$). Response times to T_1 (RT_1) were slower at the short-SOA ($F(1,6) = 25.5$, $p < .003$) for seven of the eight subjects[2]. Importantly, even though $Task_2$ was identical in each SOA condition, behavioral results showed that RT_2 was substantially longer in the short-SOA condition than in the long-SOA condition ($F(1,7) = 587.9$ $p < .0001$)[3]. Thus, the desired PRP effect was obtained. Furthermore, responses to T_2 were less accurate in the short-SOA condition than in the long-SOA condition ($F(1,7) = 29.1$ $p < .001$), as also observed by Pashler (1991).

========== Insert Table 1 about here ==========

The increase in RT_2 and reduction in T_2 accuracy as SOA was reduced suggests that central processing required for $Task_1$ interfered with some aspects of T_2 processing. To assess more precisely where the interference occurred, we measured the N2pc component elicited by T_2, which allowed us to monitor more directly the deployment of visuospatial attention. As we can observe in Figure 2c, there are clearly no effects of load on N2pc latency. Therefore, we only analysed N2pc amplitude.

The EEG was averaged starting 200 ms prior to T_2 onset and ending 500 ms after T_2 onset, and was baseline corrected on the basis of the 200 ms pre-target period. The ipsilateral waveform (average of left hemisphere with left visual field target and right hemisphere with right visual field target) and contralateral waveform (average of left hemisphere with right visual-field target and right hemisphere with left visual-field target) time-locked to T_2 for the long-SOA condition are displayed in Figure 2a and those for the short-SOA condition are shown in Figure 2b. These waveforms are different across SOA conditions because the short-SOA condition in particular includes overlapping activity elicited by $Task_1$.To isolate the N2pc from overlapping activity that was not lateralized with respect to the side of T_2 (e.g., $Task_1$ stimulus, preparation, and response activity), the N2pc was quantified as the average of the contralateral waveforms minus the average of the ipsilateral waveforms (Figure 2c). N2pc measurements (mean amplitude during the 180-260 ms post-visual display time window) were entered into an ANOVA with factors for SOA conditions (short-SOA or long-SOA) and for electrode position (O1/O2, PO7/PO8, or P7/P8). There was no interaction between electrode position and SOA, and so we report in detail only the SOA effects, which were essential to the experimental design, at PO7/PO8 sites, where the N2pc was maximal.

========== Insert Figure 2 about here ==========

The amplitude of the N2pc component was clearly reduced in the short-SOA condition relative to the long-SOA condition ($F(1,7) = 20.4$; $p < .003$). The modulation of the N2pc mean amplitude in this experiment does not seem to be caused by jitter in the latency of the component[4], and therefore strongly suggests that subjects were not able to deploy their attention on T_2 as efficiently when central attention was engaged on $Task_1$. Since the SOA conditions were randomly intermixed in each block, the modulation of the N2pc could not be caused by a differential, pre-trial preparatory state. These results are therefore consistent with the hypothesis that central attention interferes with the control of visuospatial attention.

Experiment 2

The stimulus sequences in Experiment 1 were not exactly identical across central load conditions because of the difference in SOA. ERPs can be sensitive to such differences, although it is unlikely to have produced differences in the degree of lateralization of ERPs (e.g., N2pc). Nonetheless, a second experiment was conducted in which central load was manipulated by changing the nature of $Task_1$, while holding SOA constant at 100 ms. $Task_1$ was either a speeded 4-alternative discrimination to the pitch of the tone (4AD; high-load), which was identical to $Task_1$ in Experiment 1, or a simple reaction time (SRT) response regardless of the tone (low-load). To generalize our results, a different visual display was used (see Figure 3) in which only two highly overlearned items (a letter and a digit) were presented, one on each side of fixation. The letter (A, B, C, or D) and the digit (1, 2, 3, or 4) were in different equiluminant colors (one red and one green), and the participants were required to make a speeded response to the identity of the item of a pre-specified color.

Method

Thirteen neurologically normal subjects participated in this experiment for financial compensation. Four were excluded for having no N2pc[1] (i.e., < 0.3 µV), and one more was excluded for excessive average eye movements towards the target (i.e., > .2° of residual horizontal eye movement). Therefore, 8 subjects were included in the analyses.

Stimuli and procedure where identical to Experiment 1 with the following exceptions. First, each trial was initiated by simultaneously pressing the "N" and "X" keys. Second, T_1- T_2 SOA was the same in both conditions. Third, in the SRT condition, the same speeded button-press response was required regardless of the tone. The T_1 response key in the SRT condition was counterbalanced between subjects so that all four T_1 response keys that were used in the 4AD condition (i.e., "N," "M," ",," and ".") were also used in the SRT condition. Fourth, the 100 ms visual display contained only one red and one green overlearned item (a digit and a letter) on each side of fixation, and the mask display contained two grey letters (i.e., M; see Figure 3). Half of the subjects responded to the red item in the visual display and the other half responded to the green item. Green and red items appeared randomly on the left or right of fixation. The red item was a letter for half of the subjects and a digit for the other half. All items subtended a visual angle of 1° and were presented 3° to the left or right of fixation. The letters A and B (or the digits 1 and 2) were mapped to the "Z" key and the letters C and D (or the digits 3 and 4) were mapped to the "X" key.

========== Insert Figure 3 about here ==========

Results and discussion

Behavioral results are presented in Table 1. As expected, RT_1 was faster in the SRT condition than in the 4AD condition ($F(1,7) = 39.2$ $p < .001$). Although $Task_2$ was identical in both conditions, mean RT_2 was shorter in the SRT condition than in the 4AD condition ($F(1,7) = 111.4$; $p < .0001$)[5], which demonstrates that we obtained the desired PRP effect. No T_2

accuracy effect was found (F(1,7) < 1), probably because performance approached ceiling.

Ipsilateral and contralateral waverforms at PO7/PO8 sites, as well as the difference waves for both conditions are shown in Fig.4a, 4b, and 4c. As in Experiment 1, there was no electrode (O1/O2, PO7/PO8, or P7/P8) × central load (4AD vs. SRT) interaction. Furthermore, the N2pc was completely abolished in the 4AD condition (t = -1.30; $p > .23$), resulting in a main effect of central load (F(1,7) = 9.6; $p < .018$). This result replicates N2pc results of Experiment 1, although stimuli were identical in both central load conditions.

========== Insert Figure 4 about here =========

It is interesting to note that T_2 accuracy was not affected by our manipulation of Task_1 difficulty even though the N2pc was abolished in the 4AD condition. This result suggests that visuospatial attention may not be crucial for accurate performance when identifying highly overlearned stimuli presented in a visual display with a minimal number of distractors. It is likely that stronger effects would be observed for more complex tasks and/or in the presence of a higher level of competition for processing resources, as seen in Experiment 1 (e.g., Awh, Matsukura, & Serences, 2003). We suppose that N2pc is generated by reentrant processing designed to enhance the signal-to-noise ratio of the target and that the bottom-up signals, not enhanced by the processes generating the N2pc, were sufficient to achieve a high level of performance in the present tasks.

General discussion

The amplitude of the N2pc was sharply attenuated when subjects attempted to deploy visuospatial attention while they also performed a capacity demanding speeded auditory choice task. The observed N2pc reduction was not caused by a failure of color perception per se, which is essential to locate the color-defined target towards which visuospatial attention must be deployed. Indeed, a separate behavioral control experiment was conducted in which we compared the central load effects in a condition identical to Experiment 1 (gap condition) with the central load effects in a condition with identical stimuli and an identical first task, but for which $Task_2$ was a four-alternative discrimination of the location of the uniquely colored T_2 in the visual display (location condition). A central load effect in T_2 accuracy in the gap condition but not in the location condition[6] indicated that subjects could locate the visual target as efficiently in the high-load condition than in the low-load condition, and therefore that the N2pc reduction observed in this study could not be explained by a failure of color perception in the high-load condition.

The present work is the first demonstration of interference with the N2pc response by concurrent central processing in the context of the PRP paradigm. We assume that the N2pc reflects the successful deployment of attention to the lateralized visual target (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 2003). The attenuation of N2pc caused by concurrent central processing suggests that the deployment of visuospatial attention, or the control of this process, suffered significant central interference.

The present results extend and provide converging support for related findings using the attentional blink (AB) paradigm (Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b). In the AB paradigm, accuracy of report for some aspect of a masked T_2, such as target identity, suffers when T_2 is presented at a short SOA following a T_1 that must also be processed. Jolicœur et al. (2006a, 2006b) used T_2 displays similar to the ones used in the present work following presentation of another visual stimulus (T_1) that did not require an immediate response. The N2pc was sharply attenuated by the AB. In these AB experiments, however, evidence for visual capture of attention (e.g., Folk, Leber, & Egeth, 2002) was clearly apparent in some of the results (Jolicœur et al., 2006b), and could not be ruled out completely in the other (Jolicœur et al., 2006a). That is, processing of T_1 appeared sometimes to be associated with visual capture at the location of T_1.

The present results cannot reflect visual capture because the first target in the PRP experiments was an auditory stimulus. We also do not believe that a form of cross-modal spatial capture (see McDonald & Ward, 2000) associated with the location of the source of the sound is likely. The tones, presented with a pair of speakers behind the monitor, did not appear to come from a well-localized point in space, but rather filled a large volume in the room. In any case, the present results provide clearcut evidence for the involvement of central attention because different degrees of N2pc attenuation were observed for identical stimuli (Experiment 2) associated with different tasks. Any spatial capture associated with the onset of T_1 would be the same for these stimuli. Moreover, the differential attenuation of the N2pc was also observed in absence of any possible differential pre-trial preparatory state (Experiment 1). The N2pc modulation across conditions had to be due to the different concurrent central processing demands in $Task_1$.

One could argue that the observed central load interference on the N2pc in the present study could reflect interference in task preparation after trial initiation, because the two SOAs used in Experiment 1 were very different. The interference in task preparation hypothesis would state that because participants were preparing for $Task_1$, they could not set their "color filter" as efficiently in the short-SOA condition than in the long-SOA condition. As a consequence, visuospatial attention would have been deployed on a distractor item opposite to the target, or not deployed at all, on a portion of trials. As a consequence, an attenuation of the difference in lateralized attention related activity (i.e., the N2pc) in the averaged ERPs would be predicted. Although this argument does not contradict our claim that concurrent central processing interfered with the control of visuospatial attention, because optimal preparation for $Task_2$ could not be maintained concurrently with processing required for $Task_1$, it does imply a different kind of interference than the bottleneck or capacity sharing that is postulated to be responsible for the behavioral PRP effect. The present results cannot falsify this task preparation hypothesis, and more work will be required to determine whether the interference we observed in the present work arose because of central postponement (or capacity sharing) as opposed to task preparation. However, a follow-up study (Brisson & Jolicoeur, 2007), which produced a stepwise attenuation of N2pc amplitude between SOAs of 1000, 650, and 300 ms, suggests that N2pc attenuation can be found under conditions that make differential preparation very unlikely.

Although Pashler (1991), using a very similar paradigm to the paradigm used here, concluded that central attention and visuospatial attention were independent, it is important to note that he nevertheless observed a significant reduction in T_2 accuracy between the shortest and longest SOA when color was used as the selection index (4.7%; $p < .005$) and when attention had to be deployed on the opposite side of a peripheral onset cue (5.1%; $p < .001$; see also Jolicœur & Dell'Acqua, 1999; Jolicœur, 1999a for similar SOA effects on T_2 accuracy when T_2 was masked in variants of the PRP paradigm). Several of the experiments reported by Pashler (1991) also showed evidence of interference in the form of long response times and/or decreased accuracy in $Task_1$ at short SOAs. Note that Pashler (1991) used two-alternative discrimination tasks in $Task_1$ whereas we used more demanding four-alternative discriminations, likely making our results more systematic (see Dell'Acqua & Jolicœur, 2000). The present electrophysiological results allow us to interpret these consistent SOA effects as evidence for central interference on the deployment of visual spatial attention.

Our results may appear to contradict earlier electrophysiological and behavioral results suggesting that stimuli could be processed deep in the cognitive system (to the level of meaning), without interference from bottlenecks in central processing (e.g., Vogel, Luck, & Shapiro, 1998). This contradiction is more apparent than real, however, because all previous electrophysiological work on the attentional blink, with the exception of Jolicœur et al. (2006a,b), presented stimuli at fixation, and thus could not assess the impact of central load on the deployment of visual spatial attention.

The similarity of the interaction of central load on the N2pc mean amplitude when using PRP and AB paradigms provides more evidence in support of the central interference theory (Jolicœur, 1998, 1999b) which postulates that response selection (hypothesized to be an important locus of the PRP effect) and short-term consolidation (hypothesized to be an important locus of the AB effect) have some overlap at the level of limited central mechanisms. Although our results provide clear-cut demonstrations of the interactions between central load and N2pc amplitude, further work will be required to understand these interactions in more detail. For example, at the moment we do not know whether we interfered with the displacement of the attentional locus, per se, or whether the interference was further downstream (e.g., failure to engage at the new location). Nonetheless, our new methods provide powerful tools to investigate the neural and psychological mechanisms that underlie the control of visuospatial attention.

References

Awh, E., Matsukura, M., & Serences, J. T. (2003). Top-down control over biased competition during covert spatial orienting. *Journal of Experimental Psychology: Human Perception and Performance*, **29**, 52-63.

Brisson, B., & Jolicoeur, P. (2007). A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials. *Psychophysiology*, **44**, 323-333.

Dell'Acqua, R., & Jolicœur, P. (2000). Visual encoding of patterns is subject to dual-task interference. *Memory & Cognition*, **28**, 184-191.

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 & Psychophysics*, **64**, 741-753.

Johnston, J.C., McCann, R.S., & Remington, R.W. (1995). Chronometric evidence for two types of attention. *Psychological Science*, **6**, 365-369.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded Task1 decisions. *Memory & Cognition*, **26**, 1014-1032.

Jolicœur, P. (1999a) Dual-task interference and visual encoding. *Journal of Experimental Psychology: Human Perception and Performance*, **25**, 596-616.

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

Jolicœur, P. & Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. *Psychological Research / Psychologische Forschung*, **62**, 154-164.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006a). On the control of visual spatial attention. *Psychological Research*, in press.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006b). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, **18**, 537-559.

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

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology*, **20**, 167-178.

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.

Mangun, G.R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology*, **32**, 4-18.

McDonald, J.J., & Ward, L.M. (2000). Involuntary listening aids seeing: evidence from human electrophysiology. *Psychological Science*, **11**, 167-171.

Pashler, H. (1991). Shifting visual spatial attention and selecting motor responses: distinct attentional mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, **17**, 1023-1040.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, **116**, 220-244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapoping tasks. *Quarterly Journal of Experimental Psychology*, **41A**, 19-45.

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

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 15-48.

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.

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.

Acknowlegments

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chairs Program, and the Université de Montréal awarded to PJ and by an NSERC postgraduate scholarship awarded to BB.

Footnotes

[1] Including subject(s) with no N2pc in the analyses did not change the pattern of results (i.e., did not render significant non-significant effects, or vice versa).

[2] One subject grouped his responses, and therefore presents a pattern of RT_1 that is quite different from the other subjects. We therefore excluded this subject from RT_1 analyses. However, it is known that grouping does not influence $Task_2$ performance (see Pashler and Johnston, 1989). Therefore, this subject was included in the other analysis.

[3] ANOVAs in which target side (left vs. right) was included as an additional factor revealed no main effect of target side (M_{left} = 1043, M_{right} = 1062; $F(1,7) = 1.27$, $p > .30$) nor interaction of target side with SOA ($F(1,7) = 1.46$, $p > .27$).

[4] One might wonder whether the N2pc amplitude attenuation could have been the result of a jitter in the onset of the deployment of visual-spatial in the short-SOA condition. Indeed, an all-or-none bottleneck model would predict that if central attention interfered with visuospatial attention, then the deployment of visuospatial attention on T_2 would occur only after response to T_1 has been selected. This kind of interference would result in a latency jitter of N2pc onset relative to T_2 onset. However, according to the all-or-none bottleneck model, the jitter in onset of the deployment of attention on T_2 should be minimized relative to the time of the response to T_1. Therefore, if the N2pc attenuation observed here is the result of jitter, then the N2pc should be restored in the short-SOA condition when the ERPs

are timelocked to T_1 response. N2pc-like difference waveforms timelocked to T_1 response were computed. Contrary to the jitter hypothesis, these N2pc-like difference waves were completely flat in the high-load condition in both Experiment 1 and Experiment 2, providing no support for the hypothesis that the attenuation of N2pc was due to component jitter.

[5] ANOVAs in which target side (left vs. right) was included as an additional factor revealed no main effect of target side ($F(1,7) < 1$) nor interaction of target side with central load ($F(1,7) = 1.8$; $p > .22$).

[6] T_2 accuracy for the gap condition was lower in the short-SOA condition ($M_{high\text{-}load} = 72\%$, $M_{low\text{-}load} = 82\%$; $F(1,7) = 27.4$; $p < .002$). T_2 accuracy did not vary across load in the location condition ($M_{high\text{-}load} = 91\%$, $M_{low\text{-}load} = 94\%$; $F(1,7) = 3.19$; $p > .11$). These results produced a 2-way interaction between $Task_2$ condition and SOA ($F(1,7) = 9.2$; $p < .02$).

Table 1 : Behavioral results for Experiment 1 and Experiment 2

Experiment	Experimental Condition	% correct to T_1	RT_1	% correct to T_2	RT_2
1	Short-SOA	86 (3)	854 (51)	83 (2)	1327 (52)
	Long-SOA	87 (2)	651 (30)*	88 (2)	787 (36)
2	4AD	85 (3)	870 (109)	96 (1)	1162 (76)
	SRT	100 (0)	288 (47)	94 (2)	462 (21)

RT_1 = reaction time to T_1; RT_2 = reaction time to T_2; SEM in parentheses. *See note 2.

Figure Captions

Fig. 1. Stimulus sequence in Experiment 1. In the actual experiment, the squares were red and green in the visual display and grey in the mask display.

Fig. 2. Electrophysiological results from Experiment 1. Grand average ipsilateral and contralateral ERP waveforms for (a) the high central attention load condition and (b) the low-load condition timelocked to the second target at lateral occipital PO7/PO8 sites (where the N2pc was maximal). (c) Difference waves (contralateral - ipsilateral waveforms) for both conditions.

Fig. 3. Stimulus sequence in Experiment 2. In the actual experiment, the items were red and green in the visual display and grey in the mask display.

Fig. 4. Electrophysiological results from Experiment 2. Grand average ipsilateral and contralateral ERP waveforms for (a) the high central attention load condition and (2) the low-load condition timelocked to the second target at lateral occipital PO7/PO8 sites (were the N2pc was maximal). (c) Difference waves (contralateral - ipsilateral waveforms) for both conditions.

Figure 1

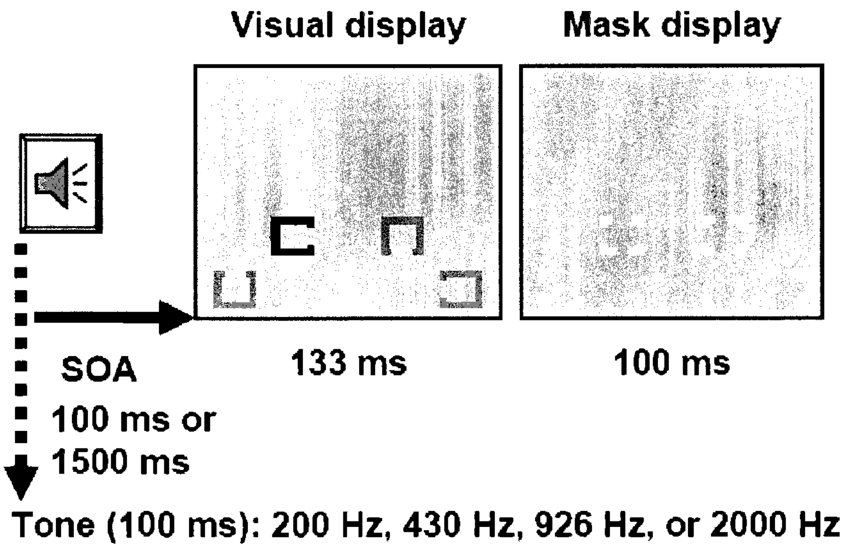

Visual display
Mask display
SOA
100 ms or
1500 ms
133 ms
100 ms
Tone (100 ms): 200 Hz, 430 Hz, 926 Hz, or 2000 Hz

Figure 2

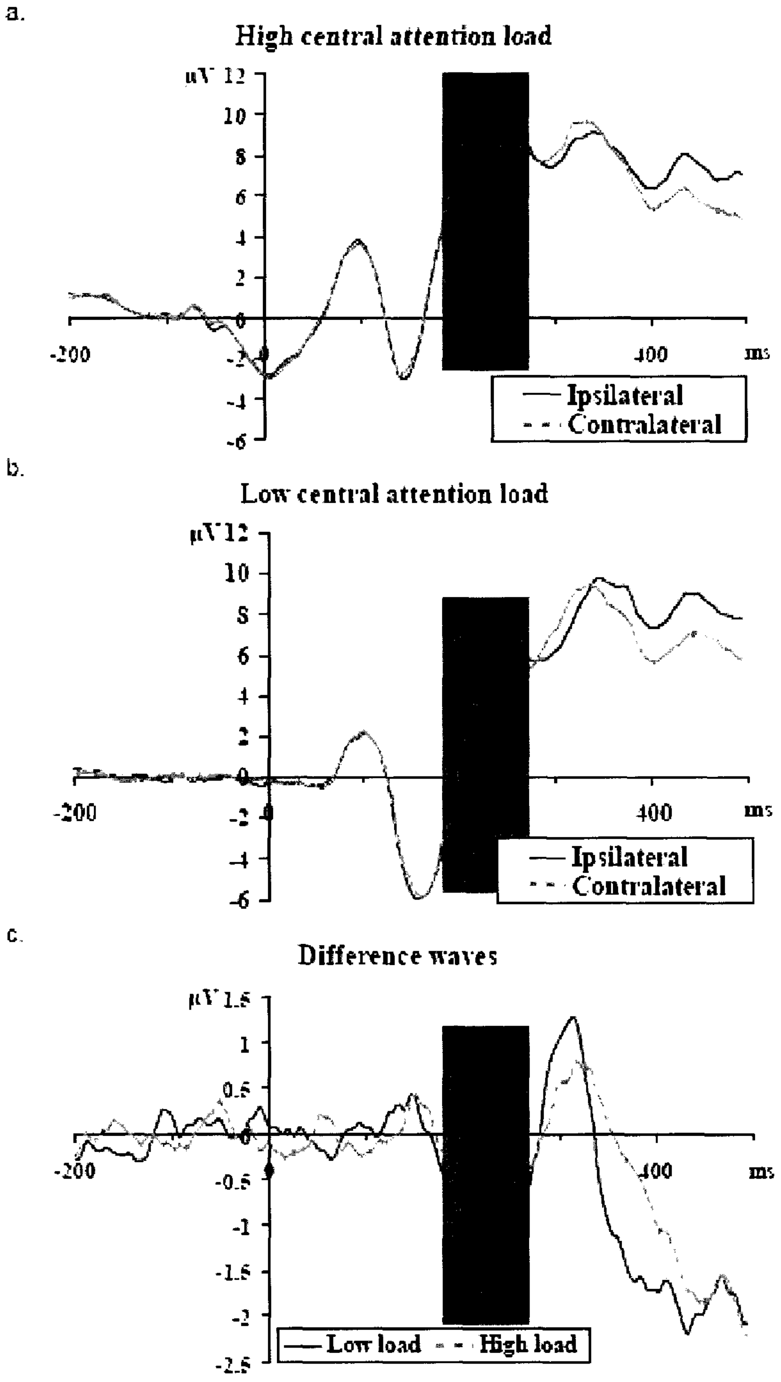

a.
High central attention load
µV 12
10
8
6
4
2
0
-2
-4
-6
-200
0
400
ms
Ipsilateral
Contralateral
b.
Low central attention load
µV 12
10
8
6
4
2
0
-2
-4
-6
-200
0
400
ms
Ipsilateral
Contralateral
c.
Difference waves
µV 1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-200
400
ms
Low load
High load

Figure 3

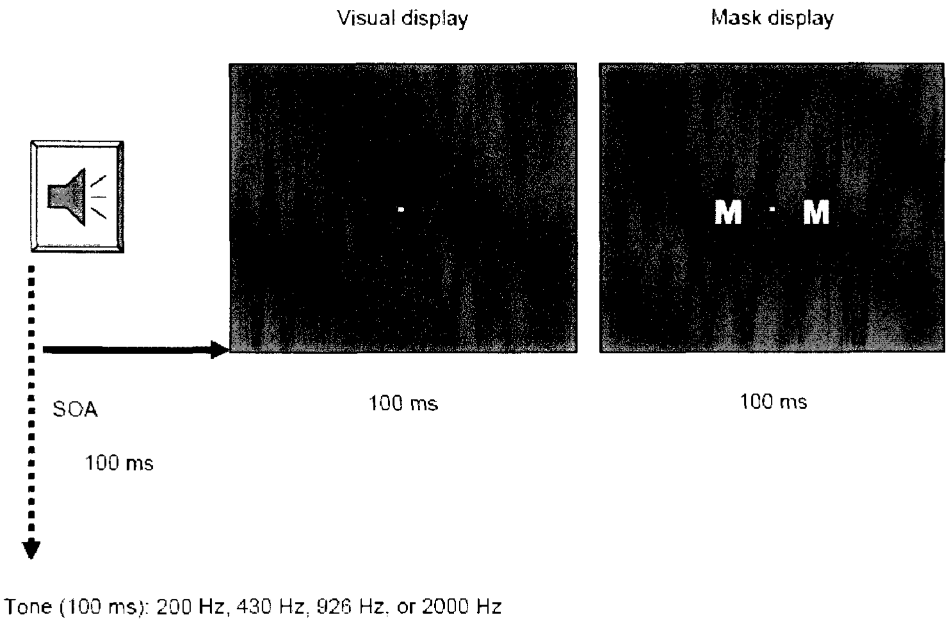
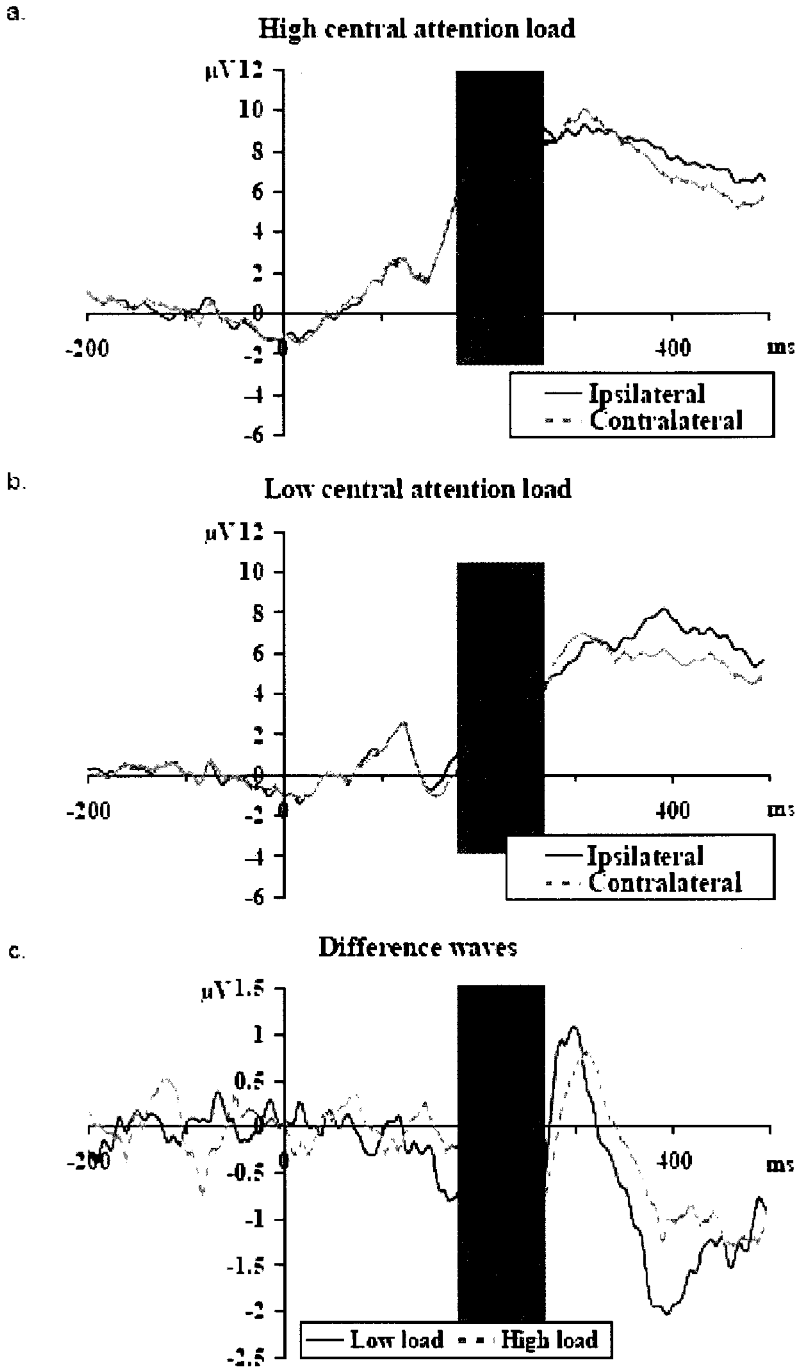

Visual display
Mask display
M · M
SOA
100 ms
100 ms
100 ms
Tone (100 ms): 200 Hz, 430 Hz, 926 Hz, or 2000 Hz

Figure 4


a.
High central attention load
µV 12
10
8
6
4
2
0
-2
-4
-6
-200
400
ms
Ipsilateral
Contralateral
b.
Low central attention load
µV 12
10
8
6
4
2
0
-2
-4
-6
-200
400
ms
Ipsilateral
Contralateral
c.
Difference waves
µV 1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-200
400
ms
Low load
High load

Article #2: A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials

A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials

Benoit Brisson and Pierre Jolicœur

Centre de recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Qc

Article published in *Psychophysiology* (2007), 44: 323—333.

Abstract

In this psychological refractory period (PRP) experiment, a tone (T_1) was presented, followed by a visual target (T_2) embedded in a bilateral display, and a speeded response was required for each target. The T_1-T_2 stimulus onset asynchrony (SOA) was 300, 650, or 1000 ms. Mean response time to T_2 increased as SOA was reduced, replicating the well-known PRP effect. Importantly, the N2pc component of the event-related potential was progressively attenuated as SOA was reduced, and the onset latency of the sustained posterior contralateral negativity (SPCN) that follows the N2pc was progressively lengthened. Conditional analysis based on Task_1 difficulty corroborated the analyses based on effects of SOA. The results suggest that central processing leading to the PRP effect interferes with the deployment of visual-spatial attention (as indexed by the N2pc) and delays encoding into VSTM (as indexed by the SPCN onset latency).

DESCRIPTORS: Cross-modal PRP paradigm, Dual-task interference, Central attention, Visual-spatial attention, Visual short-term memory, N2pc, SPCN

Introduction

Attentional limitations in multiple task situations have been studied using the psychological refractory period (PRP) paradigm. In the PRP paradigm, two distinct targets, T_1 and T_2, are presented sequentially, and a speeded response is required for each target. The processing overlap between $Task_1$ and $Task_2$ usually is manipulated by varying the temporal interval between the onset of the two targets (i.e., the T_1-T_2 stimulus onset asynchrony, or SOA). Even with very simple stimuli and associated tasks, the PRP paradigm yields robust interference effects, reflected mostly by an increase in mean response time to the second target (RT_2) as SOA is reduced (i.e., as task overlap is increased).

Several researchers have proposed that the lengthening of RT_2 (i.e., the PRP effect) is caused by a structural “bottleneck” at the stage of response selection and decision making (e.g., McCann & Johnston, 1992; Pashler & Johnston, 1989; Pashler, 1994; Welford, 1952). Specifically, the central bottleneck model postulates that, under appropriate conditions (e.g., when sensory modalities are not overloaded and when responses do not require the same output), sensory-perceptual processes and response execution processes can operate in parallel, without significant interference, for multiple targets. However, central processes such as response selection and decision making can only operate sequentially, on one target at a time. Therefore, under high task overlap conditions (e.g., at short SOAs), response selection to T_2 is postponed until central mechanisms have finished selecting the response to T_1. This postponement leads to a longer waiting period as SOA is shortened, which would explain the lengthening of RT_2. Some aspects of this model have been criticized. For example, some have argued that the central bottleneck is strategic in nature and not structural (e.g., Meyer & Kieras, 1997). Others have demonstrated that central capacity sharing models predict all the hallmark effects of the PRP paradigm, and therefore are viable alternatives to the central all-or-none bottleneck model (e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2003). However, the claim that interference in the PRP paradigm occurs at a relatively late, central locus of processing is accepted by virtually all models of dual-task interference, although recent electrophysiological evidence suggest that it may start to occur prior to response selection. Indeed, SOA effects on P3 latency have been observed (Arnell, Helion, Hurdelbrink, & Pasieka, 2004; Dell'Acqua, Jolicœur, Vespignani, & Toffanin, 2005; Luck, 1998), and this effect has been positively correlated with the behavioral PRP effect across subjects for whom a clear P3 was elicited (Dell'Acqua et al., 2005). Although the effect on P3 latency found in these previous studies was insufficient to explain all the PRP effect, it provides strong evidence that central processes prior to response selection, such as consolidation into working memory (reflected by the P3 component) can be delayed in the PRP paradigm.

Another attentional phenomenon which has been studied extensively (often referred to as visual-spatial attention) involves our ability to deploy attention to specific locations (and/or items) in the visual field without moving our eyes. Spatial cueing studies have demonstrated that performance is improved to stimuli that appear at an attended location (e.g., Posner, 1980). It is also postulated that visual-spatial attention must be deployed on individual items in a search array in order to identify a pre-defined target amongst multiple distractors, at least when the distractors and target share similar features (Duncan & Humphrey, 1989; Treisman & Gelade, 1980; Woodman & Luck, 2003a).

It has been argued that the central attentional mechanisms that underlie the PRP effect are distinct, and therefore independent, of the mechanisms involved in deploying visual-spatial attention. In an elegant chronometric study using identical critical stimuli, task, and method (i.e., the locus-of-slack logic: Jolicœur, Dell'Acqua, & Crebolder, 2001; McCann & Johnston, 1992; Pashler & Johnston, 1989; Schweickert, 1980), Johnston, McCann, and Remington (1995) demonstrated an attention restriction before the stage of letter identification in a spatial cueing paradigm, but after letter identification in the PRP paradigm. The critical stimuli were either the letter A or the letter H, and the duration of the letter identification stage was manipulated by presenting the letters either normally or distorted. The critical task was a 2-alternative speeded discrimination as to the identity of the letter (A or H). In Experiment 1, the critical task was incorporated as $Task_2$ of a PRP paradigm in which an auditory $Task_1$ was used to occupy central attention. The increased difficulty of letter identification for distorted letters had a greater effect at long SOAs than at short SOAs. According to the locus-of-slack logic, this underadditive effect of identification difficulty with decreasing SOA provides strong evidence that letter identification occurs before the stage that is delayed by allocating central attention to $Task_1$. In Experiment 2, visual-spatial attention was directed in a spatial cueing paradigm by a peripheral cue that preceded the presentation of the critical stimulus. In 80% of trials, the letter appeared at the cued location (valid condition) and in the other 20% of trials the letter appeared at the uncued location (invalid condition). The increased difficulty in identifying the letter when it was distorted had a similar effect in valid and invalid trials. According to the locus-of-slack logic, this additive effect of identification difficulty with cue validity provides strong evidence that letter identification occurs at-or-after the stage that is delayed by an invalid cue. The authors argued that visual-spatial attention and central attention are two distinct types of attention because they operate at different stages of processing. However, they investigated the two types of attention in separate experiments. This aspect of their study makes it difficult to observe possible interactions between visual-spatial attention and central attention, and consequently to determine whether or not they are truly independent.

In his seminal paper, Pashler (1991) designed a modified PRP paradigm in which $Task_2$ required a deployment of visual-spatial attention to T_2. $Task_1$ was a speeded 2-alternative discrimination of the frequency of a tone (T_1). $Task_2$ was an unspeeded 4-alternative discrimination as to the identity of T_2, which was embedded in an array of eight letters displayed in two rows of four (all letters were selected at random, without constraint, from the set A, B, C, or D). The visual array containing T_2 was subsequently masked by eight Xs displayed in the same positions previously occupied by the letters. Pashler (1991) argued that if central processing responsible for the PRP effect interferes with the deployment of visual-spatial attention, then the deployment of visual-spatial attention to T_2 would be postponed until central mechanisms are free from selecting the response to T_1. Because T_2 was masked, there was a critical time period for visual-spatial attention to be deployed to T_2 before the mask terminated sensory-perceptual processing of the items in the visual display. Following this logic, reducing SOA should result in poorer report of T_2 if both types of attention share at least some mechanisms (because of the increased postponement of the deployment of visual-spatial attention as SOA was reduced), whereas no SOA effect on report accuracy for T_2 should be observed if the two types of attention are distinct. Results showed a significant reduction in T_2 accuracy between the shortest (50 ms) and longest (650 ms) SOA when color was used as the selection index (Experiment 7: 4.7%; $p < .005$) and when attention had to be deployed on the opposite side of a peripheral onset cue (Experiment 6: 5.1%; $p < .001$). However, because these SOA effects on T_2 accuracy were much smaller than a 30% effect found when the peripheral onset cue itself was delayed (Experiment 2), Pashler concluded that the observed SOA effect on T_2 accuracy could not be caused by a lengthy period of central postponement of the deployment of visual-spatial attention. Pashler explicitly acknowledged, however, that he could not, with the behavioral methods used in his study, offer an alternative explanation of the observed significant SOA effects on accuracy in $Task_2$.

Brisson and Jolicœur (2006) recorded event-related potentials (ERPs) in addition to behavioral measures to shed new light on this important issue. The ERP component of interest in their study is called N2pc (N2 ***posterior contralateral*** : Eimer, 1996; Luck & Hillyard, 1994; Luck, Girelli, McDermott, & Ford, 1997; Woodman & Luck, 2003a). The N2pc is a lateralized ERP component that is maximal at posterior electrode sites contralateral to an attended item, and is isolated by subtracting activity at ipsilateral electrode sites from the corresponding activity at contralateral electrode sites (e.g., PO7/PO8). Although the N2pc onset latency could vary with the difficulty of target localization (Wascher, 2005), it typically starts about 180 ms post-target onset and lasts about 100 ms. Luck and colleagues, who were the first to study this component meticulously in visual search tasks, suggested that the N2pc reflected distractor suppression processes (Luck & Hillyard, 1994; Luck, Girelli, McDermott, & Ford, 1997). Others, who have used bilateral displays with only one distractor, have argued that the N2pc reflected target enhancement processes (e.g., Eimer, 1996). Nonetheless, even if there is still an ongoing debate on the specific processes that underlie the N2pc, it is widely accepted that it is a valid index of covert visual-spatial attention in light of several results reviewed by Woodman and Luck (2003a).

Brisson & Jolicœur (2006) measured the N2pc elicited by a lateralized visual target (defined by color) under different concurrent central load conditions, manipulated using a modified PRP paradigm similar to that used by Pashler (1991). A smaller N2pc was observed in high concurrent central load conditions both when central load was manipulated by varying the SOA (100 ms or 1500 ms; Experiment 1), and in a fixed 100 ms SOA PRP paradigm in which $Task_1$ difficulty was manipulated (4-alternative discrimination vs. simple reaction time; Experiment 2). The attenuation of the N2pc in this previous study provided strong evidence that concurrent central processing does in fact interfere with some aspect of the deployment of visual-spatial attention. However, because T_2 appeared more than 800 ms after mean RT_1 in the long SOA of Experiment 1, it is possible that N2pc modulations resulted from differential $Task_2$ preparation after trial initiation. Furthermore, differential pre-trial preparatory states could have accounted for N2pc modulations in Experiment 2, where attentional load conditions varied across blocks. According to this task preparation hypothesis, participants were more prepared for $Task_1$, and less prepared for $Task_2$ in the high-load condition than in the low-load condition. As a consequence, visual-spatial attention would have been deployed on a distractor item opposite to the target, or not deployed at all, on a portion of trials, leading to an attenuation of the N2pc. Although this argument does not contradict the claim that concurrent central processing interfered with the control of visual-spatial attention, because optimal preparation for $Task_2$ could not be maintained concurrently with processing required for $Task_1$, it does imply a different kind of interference than the bottleneck or capacity sharing that is postulated to be responsible for the behavioral PRP effect (Pashler, 1994; Tombu & Jolicœur, 2003).

The primary goal of the present study was to determine whether the N2pc attenuation observed in Brisson and Jolicœur (2006) arose because of central postponement (or central capacity sharing) as opposed to task preparation. To minimize the possibility of differential task preparation, three randomly presented SOAs, separated by only 350 ms, were chosen (i.e., SOAs of 300, 650, or 1000 ms). Because SOA conditions were randomly presented, it was impossible for subjects to know which condition would be presented, and therefore it was impossible for them to prepare differentially for each condition before trial initiation. Also, the post-trial task preparation hypothesis holds only if there is enough time between response to T_1 and onset of T_2 to increase $Task_2$ preparation in a long SOA condition compared to a shorter SOA condition. By choosing a difficult 4-alternative discrimination $Task_1$ that should produce long RT_1s (in the order of 700 ms; see Brisson & Jolicœur, 2006), and by separating SOAs by only 350 ms, we considerably reduce this possibility. Furthermore, because the two shortest SOAs were chosen so that T_2 would be presented usually before response to T_1, it is highly unlikely that an attenuation of the N2pc between these two SOAs would be due to differential task preparation. Therefore, a progressive attenuation of the N2pc as SOA is reduced in the present study would provide compelling evidence that central postponement (or capacity sharing) interferes with the deployment of visual-spatial attention in absence of differential task preparation.

In addition, dual-task interference associated with task overlap was also manipulated within SOA conditions by mapping four tone (T_1) frequencies arrayed from low to high to four response keys arrayed from left to right. It has been demonstrated that in these situations, it is harder to respond to the middle frequency tones than to the highest and lowest frequency tones. This difficulty effect, reflected by longer mean response times and lower accuracy to the middle frequencies than to the highest and lowest frequencies, was associated with a stage of processing that is likely in the central PRP bottleneck (see Jolicœur, 1999a; Van Selst & Johnston, 1996). Taking advantage of this built-in Task_1 difficulty manipulation, the trials in which the tones of the middle frequencies were presented were included in the hard-Task_1 condition, whereas the trials in which the tones of the highest and lowest frequencies were presented were included in the easy-Task_1 condition. An attenuation of the N2pc in the hard-Task_1 condition compared to the easy-Task_1 condition would provide further evidence against the task preparation hypothesis, because the sequence of events (i.e., SOA) in both Task_1 difficulty conditions was identical, rendering differences in task preparation based on perceived task intervals impossible.

A second important goal of this study was to discover if the sustained posterior contralateral negativity (SPCN) that follows the N2pc is affected by dual-task interference associated with task overlap. As is the case for the N2pc, the SPCN is thought to index visual activity, because it arises at electrode sites contralateral to the to-be-memorized visual items, which links the activity to the location of the task relevant items in the visual field, and has a posterior scalp distribution, which is consistent with activity in the extrastriate visual cortex (McCollough, Machizawa, &Vogel, 2006). Specifically, the SPCN is thought to reflect visual short-term memory (VSTM) activity (Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b; Klaver, Talsma, Wijers, Heinze, & Mulder, 1999; McCollough, Machizawa, &Vogel, 2006; Robitaille & Jolicœur, 2006; Vogel & Machizawa, 2004). Indeed, it has been shown that the amplitude of the SPCN increases as the number of to-be-remembered items in the visual display increases, but only up to the participants' VSTM capacity, and that it is a sustained response throughout the retention period (McCollough, Machizawa, &Vogel, 2006; Vogel & Machizawa, 2004). Furthermore, it has been found that the SPCN duration was correlated with RT in tasks that required a speeded response (Robitaille & Jolicœur, 2006). It was argued that the conditions that produced the longer RT most likely required the participants to maintain the visual trace in VSTM for a longer period, and therefore that the time course of the SPCN tracks the duration the visual trace must be held in VSTM (Prime, Chénier, & Jolicœur, 2006).

Because the SPCN reflects neural activity specifically related to the maintenance of information in VSTM, it is possible, by measuring the onset latency of the SPCN, to evaluate whether central attentional mechanisms underlying the PRP effect interfere with transfer into VSTM. If this is the case, it would provide the first demonstration that early visual memory processes are delayed by an overlapping speeded auditory task.

Methods

Participants

Twenty-four undergraduate students from the Université de Montréal participated in this experiment for financial compensation. Eight participants had to be excluded because less then 50 % of trials in at least one SOA condition remained after artefact rejection (see below). Thus 16 participants (9 women), aged 20-27 (mean age of 21.4 years) remained in the sample. All participants were neurologically intact and reported having normal hearing and normal or corrected-to-normal visual acuity and color vision.

Stimuli

Participants sat in a dimly lit, electrically shielded room, facing a computer screen, at a viewing distance of 57 cm. On each trial, a 100 ms tone (T_1), emitted simultaneously by two loudspeakers that were placed on each side of the computer screen, was followed by a 133 ms visual display that contained the second target (T_2; see Figure 1). The T_1-T_2 stimulus onset asynchrony (SOA) was 300, 650, or 1000 ms. T_1 could be at one of four frequencies (randomly presented from trial to trial: 200 Hz (68 dB), 430 Hz (60 dB), 926 Hz (60 dB), or 2000 Hz (56 dB)). The visual display contained four colored squares (two on each side of fixation), each with a gap in one side (different for each square). T_2 was a red square (x = .382, y = .275; CIE (x, y) chromaticity coordinates (Wyszecki & Stiles, 1982)) amongst green distractors (x = .277, y = .506) for half of the participants and a green square amongst red distractors for the other half. Both colors were equiluminant (26.3 cd/m^2) to equate low sensory responses and were presented on a dark-grey background (0.25 cd/m^2). All squares subtended a visual angle of 1° × 1° and the gaps were 0.33°. The centre of the squares nearest to fixation was 1.5° below and 3.5° to the left or right of fixation. The centre of the far squares was 3° below and 5° to the left or right of fixation. T_2 appeared randomly in each of the four possible positions.

========== Please insert Figure 1 about here ==========

Procedure

After hearing the four tones presented from low to high frequency five times, participants performed one practice block of 64 trials (16 single-$Task_1$ trials, 16 single-$Task_2$ trials, and 32 dual-task trials) followed by 12 experimental blocks of 64 trials.

Each trial was initiated by pressing the “N” and “V” keys simultaneously with the right and left index fingers respectively. 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. Five hundred milliseconds later, a tone (T_1) was presented (all tone frequencies were randomly presented equally often in each block), followed at an SOA of 300, 650, or 1000 ms, by a visual display that contained T_2 (all SOAs were randomly presented equally often in each block).

Two separate 4-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 location of the gap in T_2. Responses to T_1 were made with fingers of the right hand (adjacent response keys arrayed from left to right, “N,” “M,” “,,” and “.” for the 200, 430, 926, and 2000 Hz tones, respectively) and responses to T_2 were made with the fingers of the left hand (response keys were “Z,” “X,” “C,” and “V” for left, bottom, up, and right gaps, respectively). Instructions emphasized the importance to respond as quickly and accurately as possible to T_1 as soon as T_1 was presented, and to respond as quickly and accurately as possible to $T_{2,}$ as soon as T_2 was presented.

Trials ended with the simultaneous disappearance of the fixation point and appearance of the visual feedback, 1250 to 1750 ms after the response to T_2. 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 fixation point a “+” or “-” indicated a correct or incorrect response to T_2. Participants were instructed to maintain central eye fixation throughout the trial and blink only when the feedback was on the screen.

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 International 10/10 system at Fp1, Fpz, Fp2, 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. A bandpass filter of 0.01-40 Hz was applied and the EEG and EOG signals, digitized at 256 Hz, were averaged offline.

Trials with eye blinks (VEOG > 80 µV), large horizontal eye movements (HEOG > 30 µV), and/or artefacts at electrode sites of interest (i.e., > 80 µV at O1, O2, PO7, PO8, P7, and/or P8 electrode sites) were rejected. Eight participants were excluded because more then 50% of trials were rejected in at least one experimental condition. Of the remaining 16 participants, an average of 84% of 300 ms SOA trials, 82% of 650 ms SOA trials, and 80% of 1000 ms trials remained after artefact rejection. None of these participants had residual eye movements that deviated more then

0.2° (i.e., HEOG > 3.2 μV) towards T_2 after rejection criteria were applied[1] (see Luck, 2005).

The EEG was averaged starting 200 ms prior to T_2 onset and ending 600 ms post-T_2 onset, and baseline corrected based on the 200 ms pre-target period. The ipsilateral waveform (average of left-sided electrode with left visual field target and right-sided electrode with right visual field target) and contralateral waveform (average of left-sided electrode with right visual-field target and right-sided electrode with left visual-field target) time-locked to T_2 for all SOA conditions at O1/O2, PO7/PO8, and P7/P8 electrode sites were computed separately. To isolate the N2pc and the SPCN from overlapping activity that was not lateralized with respect to the side of T_2 (i.e., Task_1 stimulus, preparation, and response activity, as well as Task_2 preparation, and response activity), the N2pc and SPCN were quantified following the subtraction of the ipsilateral waveforms from the contralateral waveforms. Separate waveforms were computed also for the easy-Task_1 (lowest and highest tone frequencies) and hard-Task_1 (middle tone frequencies) conditions. To maintain an adequate number of trials per waveform, all SOAs were collapsed to compute the waveforms for the easy- and hard-Task_1 conditions.

N2pc measurements (mean amplitude during the 180-260 ms post-visual display time window) and SPCN measurements (mean amplitude during the 340-420 ms and 500-600 ms post-visual display time window) were obtained from the subtraction waveforms. SPCN onset latency measurements were also calculated using a jackknife method (Miller, Patterson, Ulrich, 1998; Ulrich & Miller, 2001). With the jackknife method, n grand average waveforms are computed with n-1 participants (a different participant is removed for each 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 must be adjusted according to

$$F_{ajusted} = F \ / \ (n-1)^2$$

(see Ulrich & Miller, 2001 for a general proof of this adjustment).

Behavioral data (mean percent accurate responses and RT for both $Task_1$ and $Task_2$) and electrophysiological measures were both submitted to two separate repeated measures ANOVAs: one in which SOA condition (300 ms, 650 ms, or 1000 ms) was treated as a within-subject factor, and another in which $Task_1$ difficulty condition was treated as a within-subject factor. Electrode position (O1/O2, PO7/PO8, or P7/P8) was included as an additional within-subject factor in the analysis performed on the electrophysiological data.

Results

Behavioral results

Only trials with correct responses to both T_1 and T_2 were included in the reaction time (RT) analyses, and outliers were excluded using the method described in Van Selts and Jolicœur (1994). RT and accuracy for each SOA and each $Task_1$ difficulty condition is presented in Table 1. Mean $Task_1$ accuracy increased as SOA increased ($F(2, 30) = 4.38$; $p < .022$). Mean RT_1

also increased with increasing SOA (*F*(2, 30) = 6.99; *p* < .004). This (slight) speed-accuracy tradeoff pattern was most likely caused by T_2 onset precipitating T_1 response before processing of the tone was complete in a portion of short SOA trials[2]. As expected, mean $Task_1$ accuracy was lower in the hard-$Task_1$ condition than in the easy-$Task_1$ condition (*F*(1, 15) = 109.2; *p* < .001) and mean RT_1 was respectively longer (*F*(1, 15) = 118.7; *p* < .001).

========== Please insert Table 1 about here ==========

As is typically observed in PRP studies where T_2 is not masked, there were no SOA effect on $Task_2$ accuracy (*F* < 1), although there was a small but reliable $Task_1$ difficulty effect (*F*(1,15) = 17.6; *p* < .001) . Importantly, RT_2 was lengthened considerably as SOA was reduced (*F*(2,30) = 91.69; *p* < .001), and was also longer for the hard-$Task_1$ condition than for the easy-$Task_1$ condition (*F*(1,15) = 26.1; *p* < .001). The observed PRP effects suggest that central processing required for $Task_1$ interfered with some aspects of processing in $Task_2$. To assess more precisely where the interference started to occur in the information processing stream in $Task_2$, we focused on the N2pc and SPCN components elicited by T_2, as described in the following section.

Electrophysiological results

N2pc

Ipsilateral and contralateral waveforms are shown in Figure 2 as a function of electrode positions and SOA, and the corresponding contralateral minus ipsilateral subtraction waveforms are presented in Figure 3. The scalp distribution of the electric potentials for the N2pc difference wave is presented in the left panel of Figure 4. The N2pc and SPCN scalp distributions were computed with the collapsed data of the two longest SOA conditions, where the components were largest. They are symmetrical about the midline because they were calculated on the basis of the contralateral minus ipsilateral difference waves used to calculate the N2pc (and SPCN). This was done specifically to avoid systematic left-right hemispheric asymmetries due, amongst others, to the fixed manual responses associated to Task_1 and Task_2. The scalp distribution of the N2pc is similar to previously published N2pc distributions (see Hopf et al., 2000; Robitaille & Jolicœur, 2006).

The analyses performed on the N2pc, which is the first large negative deflection in the subtraction waveforms, revealed a progressive attenuation of N2pc mean amplitude as SOA was reduced, reflected by a main effect of SOA ($F(2, 30) = 6.43$; $p < .015$)[3]. No main effect of electrode position ($F(2, 30) = 2.62$; $p > .10$), nor electrode position × SOA interaction ($F(4, 60) = 2.23$; $p > .10$) were found. Furthermore, when the data from the longest SOA were removed in a separate analysis, the effect of SOA on N2pc mean amplitude was still significant between the two shortest SOAs ($F(1, 15) = 19.3$; $p < .001$).

======= Please insert Figure 2, Figure 3, and Figure 4 about here =======

Contralateral minus ipsilateral subtraction waveforms as a function of electrode position and Task_1 difficulty are presented in Figure 5. N2pc mean amplitude was reduced in the hard-Task_1 condition relative to the easy-Task_1 condition ($F(1, 15) = 18.3$; $p < .001$). No main effect of electrode position ($F(2, 30) = 2.55$; $p > .10$) was observed, although an electrode position × Task_1 difficulty interaction ($F(2, 30) = 5.50$; $p < .01$) revealed a more reliable Task_1 difficulty effect at P7/P8 and PO7/PO8 electrode sites than at O1/O2 electrode sites.

========== Please insert Figure 5 about here ==========

SPCN (Sustained Posterior Contralateral Negativity)

The SPCN is the second large negative deflection in the subtraction waveforms (see Figure 3). The scalp distribution of the electric potentials for the SPCN difference wave is presented in the right panel of Figure 4. The posterior distribution of the SPCN indicates activity in the visual cortex. While the SOA effect on the N2pc was mainly reflected by an attenuation of the component, the SOA effect on the SPCN seems to be mainly reflected by an increase of the onset latency of the component as SOA was reduced (see Figure 3). To asses if the increase in the SPCN latency was significant, we proceeded in two steps. First, we calculated the mean amplitude in the 340-420 ms post-visual display time window.

The analyses revealed a main effect of SOA in this time window ($F(2,30) = 6.85$; $p < .005$), which remained when the longest SOA was removed ($F(1,15) = 7.68$; $p < .014$). As for the N2pc analyses, no main effect of electrode position ($F(2, 30) = 1.26$; $p > .29$) nor electrode position × SOA interaction ($F(4, 60) = 1.20$; $p > .31$) were observed. Then, to provide further evidence that the observed amplitude reduction in this time window was caused by a increase in the SPCN latency, an additional 10 Hz low-pass filter was applied to the subtracted waveforms and the time at which the pooled subtracted waveform reached -0.4 µV, starting at 300 ms post-visual display, was measured using the jackknife method (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). This analyses revealed a main effect of SOA on SPCN latency ($F(2, 30) = 8.53$; $p < .001$). The main effect of SOA was marginally significant in a separate analysis in which the longest SOA was removed ($F(1, 15) = 4.18$; $p < .06$).

The Task$_1$ difficulty effect on the SPCN mean amplitude in the 340-420 ms post-visual display time window was also significant ($F(1,15) = 7.99$; $p < .013$). No main effect of electrode position ($F(2, 30) = 1.21$; $p > .31$) nor electrode position × Task$_1$ difficulty interaction ($F(4, 60) = 1.20$; $p > .31$) were observed. Furthermore, as was the case with the SOA analysis, the jackknife method revealed a main effect of Task$_1$ difficulty on SPCN latency ($F(1, 15) = 4.65$; $p < .05$).

When analysing the SPCN mean amplitude in the later 500-600 ms post-visual display time window, no main effect of experimental condition ($F < 1$ for both SOA and Task$_1$ difficulty) nor any other effect was observed, which suggests that a stable VSTM representation was eventually achieved in all conditions (corroborated by the high T_2 report accuracy in all conditions).

Discussion

Two important results obtained in this study strongly suggest that central processes underlying dual-task interference in the cross-modal PRP paradigm can interfere with early sensory-specific processes. First, the N2pc was progressively attenuated as task overlap increased (i.e., as SOA decreased and as $Task_1$ difficulty within SOAs increased) between a demanding speeded auditory task and a speeded visual task that required the deployment of visual-spatial attention. Second, the onset latency of the SPCN, reflecting encoding into VSTM, following the N2pc, was progressively delayed as SOA was shortened and as $Task_1$ difficulty increased.

We assume that the N2pc reflects the successful deployment of spatial attention to the lateralized visual target (Brisson & Jolicœur, 2006; Dell'Acqua et al., 2006; Eimer, 1996; Jolicœur et al., 2006a, 2006b; Luck & Hillyard, 1994; Woodman & Luck, 2003a). The attenuation of N2pc caused by concurrent central processing suggests that the deployment of visual-spatial attention, or the control of this process, suffered significant central interference. An attenuation of the N2pc when subjects attempted to deploy visual-spatial attention while they also performed a capacity demanding speeded auditory choice task was first observed by Brisson and

Jolicœur (2006). It has been demonstrated in this previous study that the N2pc attenuation could not be caused by a PRP-induced failure of color perception. Furthermore, they argued that their results are unlikely to reflect cross-modal spatial capture (see McDonald & Ward, 2000) associated with the location of the source of the sound, because the tones, presented with a pair of speakers behind the monitor, did not appear to come from a well-localized point in space, but rather filled a large volume in the room, as in the present experiment. They also pointed out that any existing spatial capture would have been equivalent in their Experiment 2, where an N2pc modulation was observed in an experiment with a fixed 100 ms SOA. Experiment 2 also confirmed that the N2pc attenuation could not be due to ERP overlapping activity obscuring the N2pc. Indeed, sensory activity overlap was identical between the easy simple reaction time and hard 4-alternative discrimination Task_1 conditions. Moreover, greater Task_1 motor overlap in the N2pc time range would have been expected in the simple reaction time Task_1 condition, where mean RT_1 was shorter than in the 4-alternative discrimination Task_1 condition. If overlapping activity obscured the N2pc, this should have led to opposite results than those observed. Finally, in Experiment 1, where central load conditions (SOA of 100 ms vs. 1500 ms) were randomly presented, the differential attenuation of the N2pc was obtained in absence of any possible differential pre-trial preparatory state. Therefore, the N2pc modulation had to be due to the different concurrent central processing demands in Task_1. However, because T_2 appeared more than 800 ms after mean RT_1 in the long SOA condition of Experiment 1, it is possible that N2pc modulations in this earlier work resulted from differential Task_2 preparation after trial initiation, which implies a different kind of interference than the bottleneck or capacity sharing that is postulated to be responsible for the behavioral PRP effect.

The progressive attenuation of the N2pc as SOA decreased in this study, however, provides compelling evidence that differential Task_2 preparation is not the underlying cause of the observed N2pc modulation. Indeed, a differential pre-trial preparatory state was impossible because SOA conditions were randomly intermixed in each block of trials. Furthermore, the three SOAs were chosen so that the interval between the response to T_1 and T_2 onset would be too short to allow a dynamic shift in task preparation from Task_1 to Task_2. T_2 onset occurred before mean RT_1 in the two shortest SOA conditions and only 246 ms after mean RT_1 in the longest, 1000 ms, SOA condition. It would be very improbable that participants would be able to modify their processing strategy while they were still executing the first task. Moreover, mean RT_2 was about 200 ms longer in the 300 ms SOA condition than in the 650 ms condition, which means that at least 200 ms of the 350 ms difference in SOA between the two shortest SOA conditions was likely solely occupied in selecting the response to T_1, which would leave only a 150 ms difference between the two shortest SOAs to modify processing strategies. Furthermore, Task_1 performance also argues against differential preparation across SOAs. Indeed, differences in Task_1 performance across SOAs seem to indicate the presence of a slight speed-accuracy tradeoff most probably caused by T_2 onset precipitating T_1 response rather than differences in task preparation. Finally, the N2pc was also attenuated in a hard-$Task_1$ condition relative to an easy-$Task_1$ condition. Here, dual-task interference associated with task overlap was manipulated by varying $Task_1$ difficulty at each SOA, thereby making it impossible for subjects to adapt their task preparation depending on perceived T_1-T_2 SOA. Moreover, the combination of N2pc attenuation both with decreasing SOA and within SOAs (as a function of $Task_1$ difficulty) show convincingly that ERP component overlap cannot be the cause of the N2pc attenuation. This is because decreasing SOA must increase overlap, whereas increasing $Task_1$ difficulty at a given SOA must decrease overlap. Yet, both these manipulations have the same effect on N2pc amplitude, which provides new empirical evidence to support the theoretical assumption that N2pc amplitude reduction is not caused by component overlap. In combination, the evidence indicates that the all-or-none or capacity sharing bottleneck that is postulated to be responsible for the behavioral PRP effect is also responsible for the progressive N2pc attenuation as SOA was shortened (which was also significant between the two shortest SOAs), and as $Task_1$ difficulty increased.

Although the N2pc mean amplitude was progressively attenuated as task overlap increased, there was no such effect on the ultimate amplitude of the SPCN. Rather, the onset latency of the SPCN was progressively lengthened as task overlap increased (i.e., as SOA was decreased and as $Task_1$ difficulty increased within SOAs). The different patterns of N2pc and SPCN modulations provide further evidence that the N2pc and SPCN components index different processes with different functions. While the N2pc reflects visual-spatial attention processes, we assume that the SPCN reflects activity specifically related to retention in VSTM (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b; Klaver et al., 1999; McCollough, Machizawa, &Vogel, 2006; Robitaille & Jolicœur, 2006; Vogel & Machizawa, 2004). The progressive lengthening of the SPCN onset latency, therefore, suggests that transfer into VSTM was delayed by concurrent central processing responsible for the PRP effect. It is likely that the PRP effect is dominated by central postponement, because the 65 ms increase in SPCN latency between the shortest (300 ms) and longest (1000 ms) SOAs accounts for only about 27 % of the 240 ms RT_2 effect. Nevertheless, the substantial increase in the latency of the SPCN observed here is an important result because it is the first demonstration that early visual encoding processing (e.g., consolidation in VSTM) can be delayed by a demanding concurrent speeded auditory task. Although delayed, the SPCN finally reached similar amplitudes across task overlap conditions (i.e., SOA and $Task_1$ difficulty conditions), suggesting that a stable VSTM representation could eventually be achieved in all conditions, which is consistent with the high accuracy of report of T_2 in all conditions.

Recent studies have demonstrated that the N2pc was also attenuated in the attentional blink (AB) paradigm (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b). In the AB paradigm, accuracy of report for some aspect of a masked T_2, such as target identity, suffers when T_2 is presented at a short SOA following a T_1 that must also be processed. The similarity of the interaction of central load on the N2pc mean amplitude when using PRP and AB paradigms provides more evidence in support of the central interference theory (Jolicœur, 1998, 1999b) that postulates that response selection (assumed to be an important locus of the PRP effect) and short-term consolidation (postulated to be an important locus of the AB effect) have some overlap at the level of limited central mechanisms.

Although the N2pc modulations are similar when using the PRP and AB paradigms, interesting differences can be observed for the SPCN. In the AB paradigm, where dual-task interference is reflected by a decrease in T_2 report accuracy as SOA is reduced, the SPCN is also sharply attenuated (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b). In the PRP paradigm, where dual-task interference is usually reflected by an increase in RT_2 without any effect on T_2 report accuracy, the SPCN onset latency is lengthened, but finally reaches a similar amplitude in all SOA conditions. In a recent study, Woodman and Luck (2003b) demonstrated that delayed-offset four dot masking (also called object-substitution masking, Di Lollo, Enns, & Rensink, 2000), which reduces report accuracy of the masked item, does not attenuate the N2pc, but seems to have a large effect on the SPCN[4]. As in the previously mentioned AB experiments, the SPCN amplitude seemed to follow closely report accuracy. The pattern of results in this experiment are complimentary to those observed in Woodman and Luck (2003b) in that the N2pc was attenuated, while both the late portion of the SPCN (500-600 ms) and T_2 accuracy were unaffected by SOA. This double dissociation between N2pc amplitude and report accuracy suggests that conscious report is not directly correlated to a successful allocation of visual-spatial attention. On the other hand, the amplitude of the SPCN, and therefore VSTM activity, seems to be a good predictor of conscious report (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b). The present results show that encoding a visual representation in a format that supports conscious report is delayed significantly by cross-modal multitasking.

References

Arnell, K.M., Helion, A.M., Hurdelbrink, J.A., & Pasieka, B. (2004). Dissociating sources of dual-task interference using electrophysiology. *Psychonomic Bulletin & Review*, 11, 77-83.

Brisson, B., & Jolicœur, P. (2006). Electrophysiological evidence of central interference on the control of visual-spatial attention. *Psychonomic Bulletin & Review*, in press.

Dell'Acqua, R., Jolicœur, P., Vespignani, F., & Toffanin, P. (2005). Central processing overlap modulates P3 latency. *Experimental Brain Research*, 165, 54-68.

Dell'Acqua, R., Sessa, P., Jolicœur, P., & Robitaille, N. (2006). Spatial attention freezes during the attention blink. *Psychophysiology*, 43, 394-400.

Di Lollo, V., Enns, J.T., & Rensink, R.A. (2000). Competition for consciousness among visual events: The psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, 129, 481-507.

Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433-458.

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

Hopf, J.M., Luck, S.J., Girelli, M., Hagner, T., Mangun, G.R., Scheich, H., Heinze, H.J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex*, 10, 1233-1241.

Johnston, J.C., McCann, R.S., & Remington, R.W. (1995). Chronometric evidence for two types of attention. *Psychological Science*, 6, 365-369.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded Task1 decisions. *Memory & Cognition*, 26, 1014-1032.

Jolicœur, P. (1999a). Dual-task interference and visual incoding. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 596-616.

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

Jolicœur, P., Dell'Acqua, R., & Crebolder, J. (2001). The attentional blink bottleneck. In K. L. Shapiro (Ed.), *The Limits of Attention* (pp. 82-99). New York: Oxford University Press.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006a). On the control of visual spatial attention. *Psychological Research*, 70, 414-424.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006b). Attentional control and capture in the attentional blink paradigm:

Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, 18, 560-578.

Klaver, P., Talsa, 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. (1998). Sources of dual-task interference : evidence from human electrophysiology. *Psychological Science*, 9, 223-227.

Luck, S.J. (2005). ***An introduction to the event-related potential technique***. Cambridge MA: The MIT press.

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.

Luck, S.J., Girelli, M., McDermott, M.T., & 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.

McCann, R.S., & Johnston, J.C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 471-484.

McCollough, A.W., Machizawa, M.G., & Vogel, E.K. (2006) Electrophysiological measures of maintaining representations in visual working memory. *Cortex*, in press.

McDonald, J.J., & Ward, L.M. (2000). Involuntary listening aids seeing: evidence from human electrophysiology. ***Psychological Science***, 11, 167-171.

Meyer, D.E., & Kieras, D.E. (1997). A computational theory of executive cognitive processes and human multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. ***Psychological Review***, 104, 749-791.

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

Navon, D., & Miller, J. (2002). Queuing of sharing? A critical evaluation of the single-bottleneck notion. ***Cognitive Psychology***, 44, 193-251.

Pashler, H. (1991). Shifting visual spatial attention and selecting motor responses: distinct attentional mechanisms. ***Journal of Experimental Psychology: Human Perception and Performance***, 17, 1023-1040.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. ***Psychological Bulletin***, 116, 220-244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapoping tasks. ***Quarterly Journal of Experimental Psychology***, 41A, 19-45.

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

Prime, D., Chénier, H., & Jolicœur, P. (2006, April). Object representations are held in visual short-term memory during mental rotation. Poster at the Annual Meeting of the Cognitive Neuroscience Society, San Francisco, CA, USA, April 8-11.

Robitaille, N., & Jolicœur, P. (2006). Fundamental properties of the N2pc as an index of spatial attention: effect of masking. *Canadian Journal of Experimental Psychology*, 60, 101-111.

Schweickert, R. (1980). Critical-path scheduling of mental processes in a dual-task. *Science*, 209, 704-706.

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., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 15-48.

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

Van Selst, M., & Johnston, J.C. (1996, November). Dual-task interference that cannot be attributed to output interference. Paper presented at the 37th Annual Meeting of the Psychonomics Society, Chicago.

Van Selst, M., & Jolicœur, P. (1994). A solution to the effect of sample size on outlier elimination. *Quaterly Journal of Experimental Psychology: Human Experimental Psychology*, 47A, 631-650.

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

Wascher, E. (2005). The timing of stimulus localization and the Simon effect: An ERP study. *Experimental Brain Research*, 163, 430-439.

Welford, A.T. (1952). The "psychological refractory period" and the timing of high-speed performance — A review and a theory. *British Journal of Psychology*, 43, 2-19.

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

Woodman, G.F., & Luck, S.J. (2003b). Dissociation among attention, perception, and awareness during object-substitution masking. *Psychological Science*, 14, 605-611.

Wyszecki, G., & Stiles, W.S. (1982). *Color science: Concepts and methods, quantitative data and formulae* (2nd Ed.) New York: John Wiley & Sons.

Acknowledgments

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chairs Program, and the Université de Montréal awarded to PJ and by an NSERC postgraduate scholarship awarded to BB.

Footnotes

[1] The HEOG criteria was lowered to 25 μV for three participants and to 15 μV for one more participant so that the residual HEOG would be less than 3.2 μV.

[2] A subset of participants also appeared to have grouped their responses. That is, they seemed to have waited to select responses to T_2 before emitting a response to T_1 on a portion of trials. However, it is known that grouping does not influence $Task_2$ performance (see Pashler & Johnston, 1989), which is of more direct concern for the present study. Therefore, these participants were not excluded from further analyses. Response grouping, however, increases mean RT_1 as SOA is increased because these subjects waited for the presentation of T_2 before producing the response to T_1, and T_2 is presented at increasingly long delays, relative to T_1 as SOA is increased.

[3] For the electrophysiological analysis, a Greenhouse-Geisser correction was used for the estimation of F statistics associated with more than one degree of freedom in the numerator.

[4] The SPCN was not analysed in Woodman and Luck (2003b), but is visible in the presented figures.

Table 1. Mean Accuracy (percent correct) and RT (ms) to T_1 and T_2 for Each SOA (ms) Condition and Each $Task_1$ Condition.

Experimental Conditions	RT_1	ACC_1	RT_2	ACC_2
300 ms SOA	663 (45)	82.7 (2.2)	898 (53)	92.4 (2.3)
650 ms SOA	692 (51)	84.8 (2.0)	697 (38)	92.7 (2.3)
1000 ms SOA	754 (72)	85.5 (1.9)	658 (31)	92.2 (2.3)
Hard-$Task_1$	807 (58)	74.3 (2.6)	817 (51)	91.3 (2.3)
Easy-$Task_1$	633 (56)	94.3 (1.6)	706 (36)	93.5 (2.3)

RT_1 = reaction time in $Task_1$; RT_2 = reaction time in $Task_2$.

ACC_1 = accuracy for $Task_1$; ACC_2 = accuracy for $Task_2$

Standard error of the mean in parentheses.

Figure Captions

Figure 1: Stimulus sequence in each trial. Two separate 4-alternative discrimination speeded responses were required on each trial. The first response was to the pitch of the tone (T_1) and the second response was to the location of the gap in the uniquely colored square (T_2). The squares in the visual display were equiluminant red and green in the actual experiment.

Figure 2: Grand-average event-related potential (ERP) waveforms time-locked to T_2 onset at ipsilateral and contralateral P7/P8, PO7/PO8, and O1/O2 electrode sites for the 300, 650, and 1000 ms SOA conditions. All artefact-free trials, including correct and incorrect behavioral performance (see text for detail) were included in the grand-average ERPs. In this and all subsequent figures, a 15 Hz low-pass filter was applied after analysis for display purposes only.

Figure 3: Contralateral minus ipsilateral difference waves time-locked to T_2 onset at P7/P8, PO7/PO8, and O1/O2 for the 300, 650, and 1000 ms SOA conditions, and results for the pooled response over these three electrode pairs.

Figure 4: Scalp distribution of the electrical potentials measured during the N2pc (180-260 ms) and SPCN (500-600 ms) post-T_2 onset time windows. The scalp distributions were computed with the collapsed data of the two longest SOA conditions, where the components were largest, and were calculated on the basis of the contralateral minus ipsilateral difference

waves used to calculate the N2pc and SPCN, and are thus symmetrical about the midline.

Figure 5: Contralateral minus ipsilateral difference waves time-locked to T_2 onset at P7/P8, PO7/PO8, and O1/O2 for the hard-Task_1 and easy-Task_1 conditions, and the pooled response over these three electrode pairs for both Task_1 difficulty conditions.

Figure 1

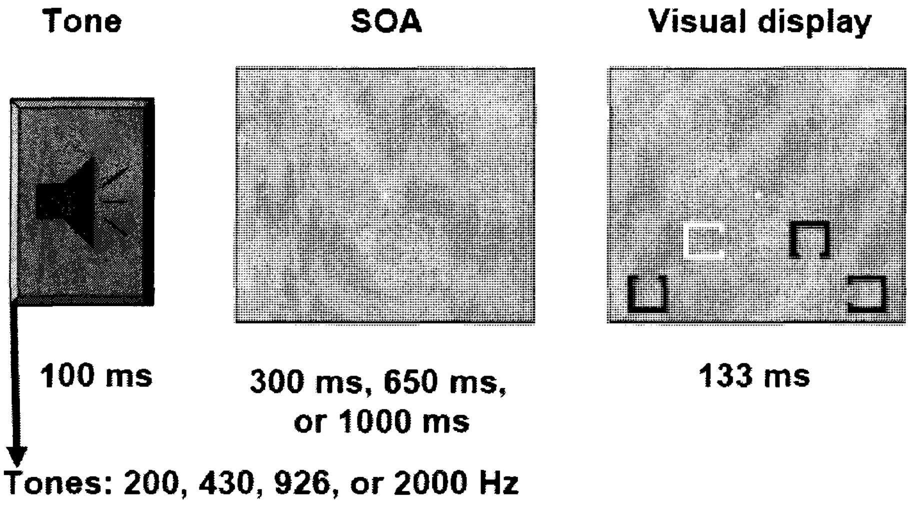

Tone
SOA
Visual display
100 ms
300 ms, 650 ms, or 1000 ms
133 ms
Tones: 200, 430, 926, or 2000 Hz

Figure 2

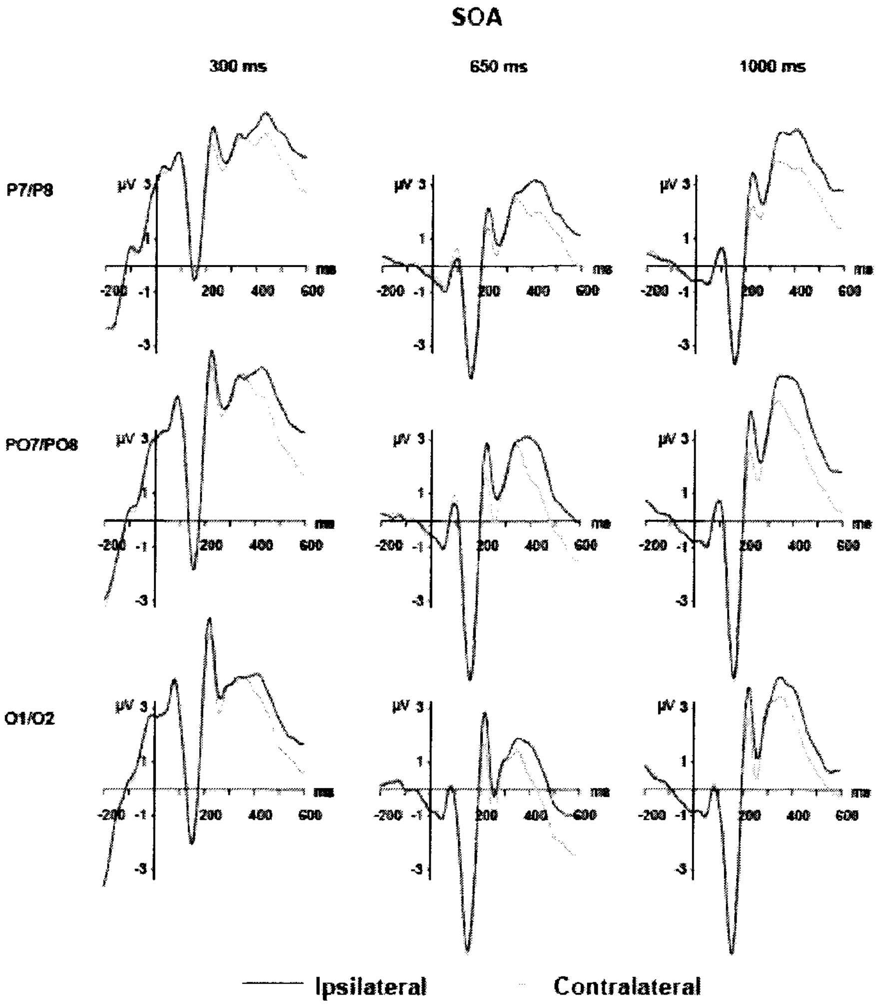

SOA
300 ms
650 ms
1000 ms
P7/P8
PO7/PO8
O1/O2
µV 3
1
-1
-3
-200
200
400
600
ms
Ipsilateral
Contralateral

Figure 3

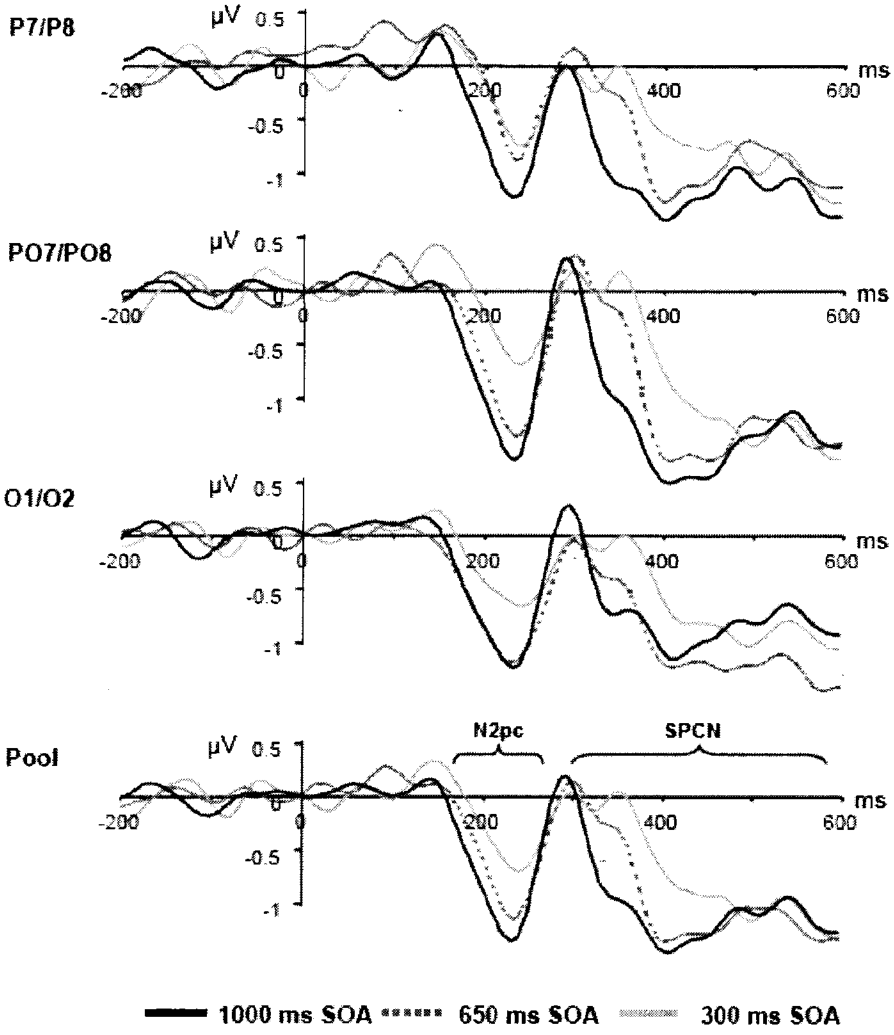
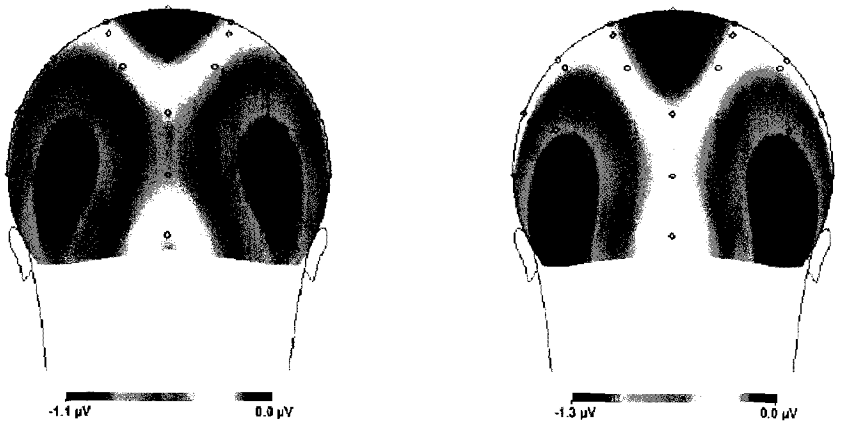

P7/P8
PO7/PO8
O1/O2
Pool
µV
0.5
0
-0.5
-1
-200
200
400
600
ms
N2pc
SPCN
1000 ms SOA
650 ms SOA
300 ms SOA

Figure 4



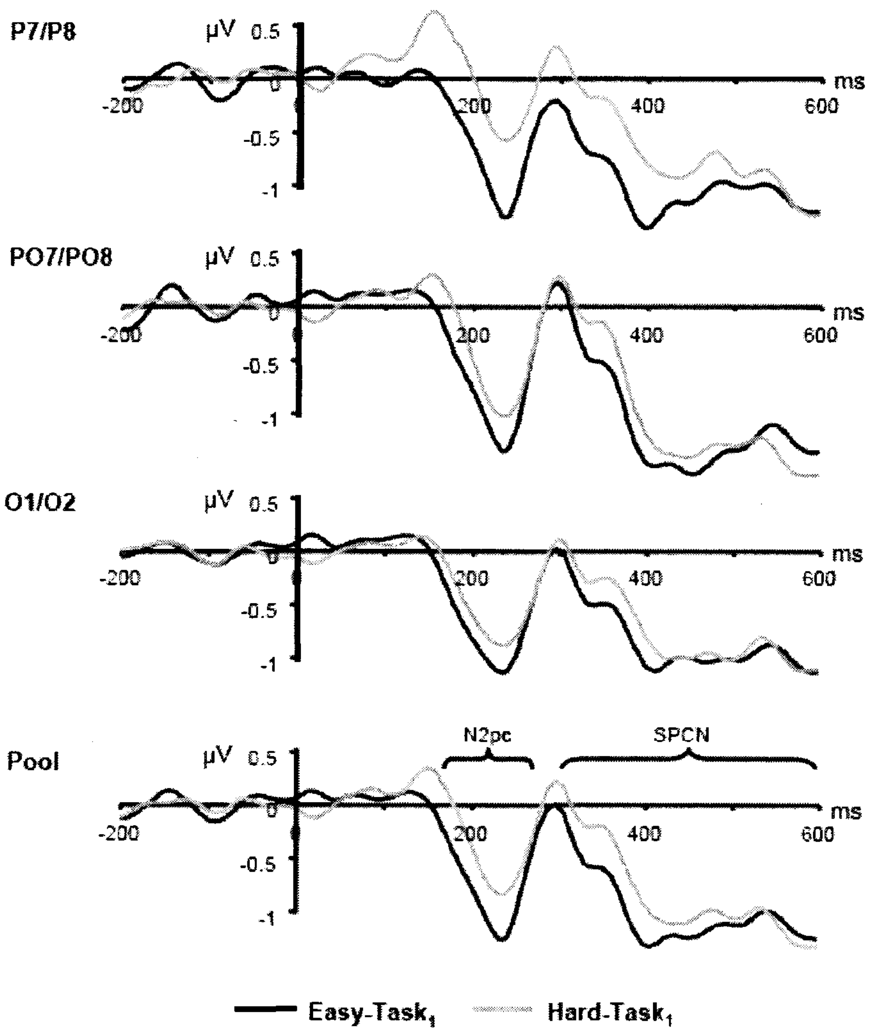
N2pc

(180-260 ms)

SPCN

(500-600 ms)

Figure 5


P7/P8
μV 0.5
0
-0.5
-1
-200
200
400
600
ms
PO7/PO8
μV 0.5
0
-0.5
-1
-200
200
400
600
ms
O1/O2
μV 0.5
0
-0.5
-1
-200
200
400
600
ms
Pool
N2pc
SPCN
μV 0.5
0
-0.5
-1
-200
200
400
600
ms
Easy-Task$_1$
Hard-Task$_1$

Article #3: Contingent capture of visual-spatial attention depends on capacity-limited central mechanisms: Evidence from human electrophysiology and the psychological refractory period

Contingent capture of visual-spatial attention depends on capacity-limited central mechanisms: Evidence from human electrophysiology and the psychological refractory period

Benoit Brisson, Émilie Leblanc, and Pierre Jolicœur

Centre de recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Qc

Article in press in ***Biological Psychology***

Abstract

It has recently been demonstrated that a lateralized distractor that matches the individual's top-down control settings elicits an N2pc wave, an electrophysiological index of the focus of visual-spatial attention, indicating that contingent capture has a visual-spatial locus. Here, we investigated whether contingent capture required capacity-limited central resources by incorporating a contingent capture task as the second task of a psychological refractory period (PRP) dual-task paradigm. The N2pc was used to monitor where observers were attending while they performed concurrent central processing known to cause the PRP effect. The N2pc elicited by the lateralized distractor that matched the top-down control settings was attenuated in high concurrent central load conditions, indicating that although involuntary, the deployment of visual-spatial attention occurring during contingent capture depends on capacity-limited central resources.

DESCRIPTORS: Contingent capture, Cross-modal PRP paradigm, Dual-task interference, N2pc, Human electrophysiology

Introduction

At any given moment, our visual world offers us a large amount of information, far more than what can be processed at one time by our capacity-limited cognitive system. It is therefore crucial to identify and isolate efficiently a subset of objects or a region of the visual field suspected of containing relevant information, so that this information can benefit from preferential processing, and ultimately guide our actions. This selection is accomplished by attentional mechanisms that can act at early or late stages of processing, depending on the stimuli and task at hand (see Luck, Woodman, & Vogel, 2000).

One type of attention that has been studied extensively is often referred to as visual-spatial attention. Numerous studies have demonstrated that performance is improved when stimuli appear at an attended location (Posner, 1980; Jonides, 1981; Müller & Rabbitt, 1989). It is also postulated that visual-spatial attention must be deployed on individual items in a search array in order to identify a pre-defined target amongst multiple distractors, at least when the distractors and target share similar features (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Woodman & Luck, 2003). It is well known that visual-spatial attention can be deployed voluntarily to specific locations (and/or items) in the visual field, according to the individual's goals, or can be captured by a sufficiently intense and salient stimulus, independently of the individual's volition. An item can also capture attention if it matches the individual's top-down attentional control settings, that is to say, if it shares a characteristic that is relevant for attentional selection, even if the item itself is task-irrelevant. For example, if an observer's task is to respond to a red target, the presentation of a concurrent red distractor will often impair performance, but the presentation of a blue or yellow distractor will not (Folk, Leber, & Egeth, 2002; Folk & Remington, 1998; Lamy, Leber, & Egeth, 2004; Leblanc & Jolicoeur, 2005; Serences, Shomstein, Leber, Golay, Egeth, & Yantis, 2005). Such contingent capture effects have been observed for color, shape, movement, and sudden onset (Bacon & Egeth, 1994; Folk, Remington, & Wright, 1994). Recent electrophysiological studies have demonstrated that distractors that share the relevant attentional selection characteristic generate an N2pc (N2 ***posterior contralateral***) component (Leblanc, Prime, & Jolicoeur, 2008), as do both salient task-irrelevant singletons (Hickey, McDonald, & Theeuwes, 2006; although this effect can be overridden in the presence of a specific task set, if the singleton is very different from the target, see Luck & Hillyard, 1994), and voluntarily attended items (Eimer, 1996; Luck & Hillyard, 1994; Luck, Girelli, McDermott, & Ford, 1997; Woodman & Luck, 2003). The N2pc is a lateralized event-related potential (ERP) component that typically occurs about 180-280 ms after the onset of a visual display and is maximal at posterior electrode sites contralateral to an attended item. Because the N2pc likely indexes covert visual-spatial attention (for a review, see Woodman & Luck, 2003), the Hickey et al. (2006) and Leblanc et al. (2008) studies convincingly demonstrated that capture by highly salient task-irrelevant singletons and contingent capture share at least some underlying visual-spatial attention mechanisms that are similar to voluntary visual-spatial attention mechanisms. In addition, several earlier studies using spatial cuing paradigms combined with the ERP technique strongly suggest that stimuli that appear in the focus of attention benefit from enhanced early sensory-perceptual processing (indexed by the P1 and/or N1 components), independently of whether visual-spatial attention is deployed voluntarily or captured involuntarily by a salient peripheral onset cue (Hopfinger & Mangun, 1998, 2001; Mangun, 1995; Mangun & Hillyard, 1991).

Another type of attention that has been extensively studied, often referred to as central attention, involves our limits in performing concurrent multiple tasks. The psychological refractory period (PRP) paradigm has been used extensively to study multitasking attentional limitations. In the PRP paradigm, two distinct targets, T_1 and T_2, are presented sequentially, and a speeded response is required for each target. The processing overlap between $Task_1$ and $Task_2$ usually is manipulated by varying the temporal interval between the onset of the two targets (i.e., the T_1-T_2 stimulus onset asynchrony, or SOA). Even with very simple stimuli and associated tasks, the PRP paradigm yields robust interference effects, reflected mostly by an increase in mean response time to the second target (RT_2) as SOA is reduced (i.e., as task overlap is increased). Virtually all models of dual-task interference claim that interference in the PRP paradigm occurs at a relatively late, central locus of processing, such as response selection and decision making (e.g., Pashler, 1994; Tombu & Jolicœur, 2003).

Based on behavioral evidence, some researchers claimed that visual-spatial attention and central attention are independent (e.g., Jonhston, McCann, & Remington, 1995; Pashler, 1991). However, in recent electrophysiological studies, Brisson and Jolicœur (2007a, 2007b, 2007c) measured the N2pc elicited by a lateralized visual target (defined by color) under different task overlap conditions using audio-visual cross-modal PRP paradigms, and observed a smaller N2pc in high concurrent central load conditions, that is to say, with shorter T_1-T_2 SOAs or a more difficult task associated with T_1. The N2pc was quantified following the subtraction of the ipsilateral waveforms from the contralateral waveforms, eliminating all overlapping activity that was not lateralized with respect to the side of T_2 (i.e., $Task_1$ stimulus, preparation, and response activity, as well as T_2 display onset, and $Task_2$ preparation, and response activity). Therefore, the N2pc attenuation in these studies could not have been caused by overlapping $Task_1$ activity obscuring the N2pc[1]. Brisson and Jolicœur (2007a) have also demonstrated that the N2pc attenuation could not have been caused by a PRP-induced failure of color perception, nor by cross-modal spatial capture by the tone (McDonald & Ward, 2000). Therefore, the N2pc attenuation in high concurrent central load conditions observed in Brisson and Jolicœur (2007a, 2007b) provided strong evidence that concurrent central processing of a tone interferes with the voluntary deployment of visual-spatial attention, and therefore that at least the voluntary deployment of visual-spatial attention requires central resources.

The goal of the present study was to determine whether the contingent involuntary deployment of visual-spatial attention, occurring in response to a task-irrelevant distractor sharing the relevant attentional selection characteristic, also requires capacity-limited central resources. To accomplish this goal, the contingent capture task used in Leblanc et al. (2008; Experiment 4) was incorporated as the second task of an audio-visual PRP paradigm, and the N2pc elicited by the lateralized distractor that matched the observers' top-down attentional control settings was measured in different concurrent central load conditions, manipulated with SOA. In this particular contingent capture task, only two peripheral distractors are presented, in the left and right visual fields. One distractor is grey, and the other is colored. In half the trials, the colored distractor shares the target-defining attribute, that is to say, its color. This symmetrical configuration allows the measurement of the N2pc in a balanced display on the sensory level. Moreover, because there are only two distractors and that each of them is uniquely colored, it ensures that the effect of the target-colored distractor is due to the contingency between the distractor's color and the top-down attentional control settings in favour of the target color, and not to the singleness of the colored distractor.

Measuring the N2pc was essential, not only because it provided a direct moment-by-moment index of the locus of visual-spatial attention, but also because behavioral results alone can lead to opposite interpretations. The present study was designed so that contingent capture would be reflected principally by a decline in accurate report of the second visual target when preceded by a target-colored distractor compared to when it is preceded by a nontarget-colored distractor. To determine whether the involuntary deployment of attention underlying contingent capture requires central resources, we would need to look at the interaction between the distractor color condition (target-colored distractor vs. nontarget-colored distractor) and the SOA condition. At least two patterns of results could be expected: an underadditive effect of distractor color with decreasing SOA, or an additive effect. Although it could be tempting to interpret an underadditive effect as evidence that concurrent central processing blocked the deployment of attention to the target-colored distractor, thus reducing contingent capture, this pattern of results would also be predicted if the involuntary deployment of attention was independent from central resources, had time to be deployed to the distractor location and return to fixation before central processing was freed from the first task. On the other hand, it could be tempting to interpret an additive effect as an indication that contingent capture of visual-spatial attention was not affected by SOA, and therefore that the involuntary deployment of visual-spatial attention, occurring during the contingent capture of attention, does not require central resources. However, an additive effect could also indicate that contingent capture of visual-spatial attention was reduced at the shortest SOA, that is to say, that visual-spatial attention was not drawn, or not to the same extent, to the location of the target-colored peripheral distractor, but that this effect was counterbalanced by an opposite effect. For example, it has been demonstrated that during the PRP period short-term consolidation of T_2 is delayed (Jolicœur & Dell'Acqua, 1998) and that before it gains access to short-term memory, T_2 representation is susceptible to decay, leading to a decrease in T_2 accuracy as SOA decreases when T_2 is masked in variants of the PRP paradigm (Brisson & Jolicœur, 2007a; Jolicœur, 1999; Jolicœur & Dell'Acqua, 1999, Pashler 1991). Therefore, if the difficulty of selecting the item to be consolidated in short-term memory (i.e., the target) depends on the number of items that possess the target defining characteristic (i.e., selection of the target would be more difficult when a target-colored distractor is also presented), and that this selection difficulty increases as T_2 representation decays (i.e., as SOA decreases), we would predict a pattern of results opposite to a reduction of contingent capture. Specifically, we would predict a PRP effect on T_2 performance (i.e., longer RTs accompanied by lower accuracy in the short SOA condition when T_2 is masked), and an orthogonal behavioral effect analogous to a contingent capture effect (i.e., longer RTs and/or lower accuracy in the target-colored distractor condition), except that while this last effect would be due to a shift of visual-spatial attention to the distractor location in low concurrent central load condition (long SOA), in the high concurrent central load condition (short SOA), it would rather be caused by an increased difficulty of selecting the item to be consolidated in short-term memory (i.e., the target) in the presence of a target-colored distractor.

Contrary to the behavioral measures, the N2pc provides a direct measure of the deployment of visual-spatial attention, and as such provides an unambiguous tool to answer our question. If contingent capture of visual-spatial attention does not depend on limited central attentional resources, as would be intuitively expected considering the involuntary nature of attentional capture, the N2pc should be identical in all SOA conditions. On the other hand, if contingent capture of visual-spatial attention does depend on limited central attentional resources, despite its involuntary nature, then we predict that the N2pc should be attenuated at short SOAs (i.e., in high concurrent central load conditions), as was observed for the voluntary deployment of visual-spatial attention (Brisson & Jolicoeur, 2007a, 2007b, 2007c). However, a delay of the N2pc onset could also be observed at the short SOA if the deployment of visual-spatial attention to the distractor location is postponed until central processes are freed from the first task, as would be predicted by a bottleneck account. It is also possible that it is more difficult to maintain visual-spatial attention on the vertical midline under high concurrent central load conditions, leading to greater capture of visual-spatial attention, and consequently to a larger N2pc at short than at long SOAs.

Given that the goal of the present study was to investigate possible modulations of the amplitude and onset latency of the N2pc, it was important to choose a contingent capture task that maximized the amplitude of the N2pc in the low concurrent central load condition. We therefore chose to use the contingent capture task in Leblanc et al. (2008) that produced the largest contingent capture N2pc. It is worth mentioning, however, that in the selected experiment (Experiment 4) the N2pc was preceded by a contralateral positivity in the P1 time-range. This contralateral positivity was not associated with a particular distractor condition or with the attentional control settings required to perform the task. Consequently, it is unlikely that this effect is related to either attention orienting or to the observed pattern of behavioral performance. Moreover, it was only present in Experiments 1 to 4 of the Leblanc et al. (2008) paper, where the colored distractor was always presented with a grey distractor, and where the colored distractor was presented in the target color more often than in any of the three nontarget colors. Indeed, in their Experiment 5, where the two peripheral distractors were always colored, and each color was used equally often, the contralateral positivity that preceded the N2pc was eliminated, suggesting that it was linked to a contextual imbalance, regarding the relative frequency of presentation of each color and grey in the periphery, even though each distractor display was balanced on the sensory level (every color and grey were equiluminant). Because the contralateral positivity likely reflects an early contextual perceptual effect, it should not be modulated by central load. Therefore, the presence of this contralateral positivity, which was expected, is secondary, and should be orthogonal, and thus inconsequential to our principal goal, which was to focus on the N2pc.

Methods

Participants

Thirty-five undergraduate students from the Université de Montréal participated in this experiment for financial compensation. Eleven participants were excluded for reasons outlined below, leaving 24 participants (14 women), aged 19-30 years (mean age: 21.5 years) in the final sample. All participants were neurologically intact and reported having normal hearing and normal or corrected-to-normal visual acuity and color vision.

Stimuli

Participants sat in a dimly lit, electrically shielded room, facing a computer screen, at a viewing distance of 57 cm. On each trial, a 100 ms tone (T_1) was emitted simultaneously by two loudspeakers that were placed on each side of the computer screen. On two thirds of trials, T_1 was followed by a sequence of three visual displays: 1) a 117 ms distractor display, 2) an 83 ms visual target (T_2) display, and 3) a 117 ms mask display (see Figure 1). On the other third of trials, the distractor display was replaced by a blank interval. The stimulus onset asynchrony (SOA) between T_1 and the distractor display (or the blank interval) was 200, or 500 ms, each randomly presented equally often in each block. There was no interstimulus interval between the distractor display (or the blank interval) and the T_2 display, nor between the T_2 display and the mask display.

T_1 could be at one of four frequencies randomly presented equally often in each block: 200 Hz [68 dB], 430 Hz [60 dB], 926 Hz [60 dB], or 2000 Hz [56 dB].

The distractor display consisted of two 1.3° of visual angle high "#" symbols, one in each visual hemifield, presented 2° to the left or right of fixation, measured center-to-center. One "#" symbol was grey and the other was colored (see next paragraph for color specifications). The location, left versus right, of the colored distractor varied randomly across trials. In the Target-color Distractor Condition, the colored symbol had the same color as the target digit presented in the T_2 display. In the Nontarget-color Distractor Condition, the color of the colored symbol was selected at random from the nontarget colors on each trial. Distractor conditions were randomly presented equally often in each block.

The visual target (T_2) display consisted of the simultaneous presentation of three different digits presented on the vertical midline in the center of the computer screen. Each of the digits (randomly selected from the digits 2 through 9) within the T_2 display were 1.3° of visual angle high and colored either red, blue, green, or ochre. The four colors and grey were equiluminant (12.8 cd/m^2, as measured by a Minolta CS-100 luminance meter). One of the four colors was designated as the target color for each participant. The visual target was the digit within this display that was presented in the pre-specified target color. Target color was counterbalanced across subjects and the colors of nontarget digits were selected at random from the three nontarget colors. The vertical position of the target digit was selected at random on each trial.

The mask display consisted of three grey 1.3° high "W" characters, presented at the locations where the three digits had appeared.

========== Please insert Figure 1 about here ==========

Procedure

After hearing the four tones presented from low to high frequency five times, participants performed one practice block of 40 trials followed by 13 experimental blocks of 80 trials. Each block consisted of 32 Target-color Distractor trials (half were 200 ms SOA trials and half were 500 ms SOA trials), 32 Nontarget-color Distractor trials (half were 200 ms SOA trials and half were 500 ms SOA trials), and 16 Distractor-Absent trials (half 200 ms SOA, half 500 ms SOA). This amounted to 208 trials for each of the four Distractor (Target-color Distractor vs. Nontarget-color Distractor) × SOA (200 ms vs. 500 ms) cells, and 104 Distractor-Absent trials.

Each trial was initiated by pressing the spacebar. Feedback from the preceding trial disappeared. Two hundred milliseconds later, a tone (T_1) was presented, followed, at an SOA of 200 ms or 500 ms, by the visual display sequence that comprised 1) the distractor display or a blank interval, 2) the T_2 display, and 3) the mask display.

Two separate speeded responses were required on each trial. The first was a four-alternative speeded response to the pitch of T_1 and the second was an eight-alternative speeded response to the identity of T_2. Responses to T_1 were made with fingers of the left hand (adjacent response keys arrayed from left to right, “Z,” “X,” “C,” and “V” for the 200, 430, 926, and 2000 Hz tones, respectively) and responses to T_2 were made with the right hand using the numeric keypad. Instructions emphasized the importance to respond as quickly and accurately as possible to T_1 as soon as T_1 was presented, and to respond as quickly and accurately as possible to T_2, as soon as T_2 was presented. Participants were also instructed to ignore the lateral distractors.

Trials ended with the appearance of visual feedback after the response to T_2. 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 fixation point a “+” or “-” indicated a correct or incorrect response to T_2. Participants were instructed to maintain central eye fixation throughout the trial, to respond without moving their eyes, and to blink only when the feedback symbols were on the screen.

EEG Recording and Analysis

The EEG was recorded from 64 active Ag/AgCl electrodes (BioSemi ActiveTwo system) mounted on an elastic cap and referenced to the average of the left and right mastoids. Electrodes were placed according to the International 10/10 system at Fp1, Fpz, Fp2, 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. A lowpass filter of 40 Hz was applied and the EEG and EOG signals, digitized at 256 Hz, which were averaged offline.

Trials with eye blinks (VEOG > 80 μV), large horizontal eye movements (HEOG > 30 μV), and/or artefacts at electrode sites of interest (i.e., > 80 μV at PO7, and/or PO8 electrode sites) were rejected. Six participants were excluded because more then 35% of trials were rejected in at least one of the four distractor color × SOA cells. Five more participants were excluded because accuracy in $Task_1$ and/or $Task_2$ was less than 50% correct. Of the remaining 24 participants, an average of more than 90% of trials remained after artefact rejection in all Distractor color × SOA conditions. None of these participants had residual eye movements that deviated more then 0.2° towards the colored distractor after rejection criteria were applied (see Luck, 2005).

The EEG was averaged starting 200 ms prior to the distractor display onset and ending 500 ms after distractor display onset, and baseline corrected based on the 200 ms pre-distractor display period. The ipsilateral waveform (average of left-sided electrode with left visual field colored distractor and right-sided electrode with right visual field colored distractor) and contralateral waveform (average of left-sided electrode with right visual-field colored distractor and right-sided electrode with left visual-field colored distractor), time-locked to the onset of the distractor display for all four Distractor × SOA Conditions, were computed separately. To isolate the N2pc from overlapping activity that was not lateralized with respect to the side of the colored distractor (i.e., Task_1 stimulus, preparation, and response activity, as well as T_2 display onset, and Task_2 preparation, and response activity), the N2pc was quantified following the subtraction of the ipsilateral waveforms from the contralateral waveforms.

The N2pc (mean amplitude during the 200-250 ms post-distractor display onset time window) and the contralateral positivity in the P1 time-range (mean amplitude during the 110-160 ms post-distractor display onset time window) were measured from the subtraction waveforms at PO7 and PO8 electrode sites, were the N2pc was maximal. N2pc onset latency measurements were also calculated using a jackknife method (Kiesel, Miller, Jolicoeur, & Brisson, 2008; Miller, Patterson, Ulrich, 1998; Ulrich & Miller, 2001). With the jackknife method, n grand average waveforms are computed with n-1 participants (a different participant is removed for each 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 must be adjusted according to

$$F_{\text{ajusted}} = F / (n-1)^2$$

(see Ulrich & Miller, 2001 for a general proof of this adjustment).

Behavioral data (mean percent accurate responses and RT for both Task_1 and Task_2) were submitted to repeated measures ANOVAs in which Distractor Condition (Distractor-Absent vs. Target-color Distractor vs. Nontarget-color Distractor) and SOA Condition (200 ms vs. 500 ms) were treated as within-subject factors. Electrophysiological measures were submitted to one sample *t*-tests versus zero, and to repeated measures ANOVAs in which Distractor Condition (Target-color Distractor vs. Nontarget-color Distractor) and SOA Condition (200 ms vs. 500 ms) were treated as within-subject factors. The N2pc measurements in the Target-Color Distractor Condition were also submitted to a repeated measures ANOVA in which SOA Condition (200 ms vs. 500 ms) was treated as within-subject factor.

Results

Behavioral results

Only trials with correct responses to both T_1 and T_2 were included in the reaction time (RT) analyses, and outliers were excluded using the method described in Van Selst and Jolicœur (1994). RT and accuracy for each Distractor Condition × SOA cell for each task is presented in Table 1. Mean Task_1 accuracy increased as SOA increased ($F(1, 23) = 9.73$; $p < .005$), as did mean RT_1 ($F(1, 23) = 19.01$; $p < .001$), indicating a (slight) speed-accuracy tradeoff pattern in Task_1. Mean Task_1 accuracy was higher in the Distractor-Absent Condition than in the Nontarget-color Distractor Condition, and higher in the Nontarget-color Distractor Condition than in the Target-color Distractor Condition, resulting in a main effect of Distractor Condition on Task_1 accuracy ($F(1, 23) = 5.35$; $p < .009$). Mean RT_1 was similar across Distractor Conditions ($F(1, 23) = 1.03$; $p > .36$). No Distractor Condition × SOA interaction was observed in either Task_1 accuracy or RT_1 (both *F*s < 1).

========== Please insert Table 1 about here ==========

Task_2 accuracy was significantly worse in the Target-color Distractor Condition than in the Nontarget-color Distractor or in the Distractor-Absent Conditions ($F(2, 46) = 8.28$, $p < .001$), replicating the contingent capture effect. Task_2 accuracy was also significantly worse in the 200 ms SOA Condition than in the 500 ms SOA Condition ($F(1, 23) = 5.57$, $p < .03$), as is often observed in PRP studies were T_2 is masked. No Distractor Condition × SOA interaction was observed on Task_2 accuracy ($F < 1$).

Finally, RT_2 lengthened considerably as SOA was reduced ($F(1, 23) = 92.15$; $p < .001$), replicating the well-known PRP effect. No main effect of

Distractor Condition or Distractor Condition × SOA interaction was observed on RT_2 (both *F*s < 1).

Electrophysiological results

Ipsilateral and contralateral waveforms at PO7/PO8 electrode sites are shown in Figure 2 as a function of SOA, and Distractor Condition, and the corresponding contralateral minus ipsilateral subtraction waveform is presented in Figure 3.

One sample *t*-tests versus zero revealed that a significant N2pc was elicited in the Target-color Distractor Condition [$t(23) = -4.79$, $p < .001$ and $t(23) = -2.55$, $p < .02$ in the 500 ms and 200 ms SOA Conditions, respectively], but not in the Nontarget-color Distractor Condition [$t(23) = -0.35$, $p > .72$ and $t(23) = -1.85$, $p > .075$ in the 500 ms and 200 ms SOA Conditions, respectively]. Furthermore, this resulted in a main effect of Distractor Condition on N2pc mean amplitude ($F(1, 23) = 6.39$, $p < .004$). We thus replicated the electrophysiological effect associated with contingent attentional capture, showing that the presentation of a target-colored distractor elicits a shift of visual-spatial attention to the location it occupies, which was not the case for an equally salient nontarget-colored distractor.

Importantly, a significant Distractor Condition × SOA interaction was observed ($F(1, 23) = 10.07$, $p < .004$). This interaction was driven by a main effect of SOA on N2pc mean amplitude when only the Target-color Distractor Condition was considered ($F(1, 23) = 7.06$, $p < .014$). To analyse possible SOA effects on N2pc latency, an additional 15 Hz low-pass filter was applied to the subtracted waveforms in the Target-color Distractor condition and the time at which the pooled subtracted waveforms reached -0.3 µV, starting at 160 ms post-distractor display, was measured using the jackknife method (Kiesel et al., 2008; Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). This analyses failed to reveal a main effect of SOA on N2pc latency ($F_{adjusted}(1, 23) = 2.58$; $p > .12$).

Figure 4 shows the scalp distribution of the electric potentials for the N2pc difference wave elicited in the Target-color Distractor Condition as a function of SOA, as well as the scalp distribution for the N2pc effect, computed from the 500 ms SOA minus 200 ms SOA N2pc difference waves. These scalp distributions are symmetrical about the midline because they were calculated on the basis of the contralateral minus ipsilateral difference waves used to calculate the N2pc. This was done specifically to avoid systematic left-right hemispheric asymmetries due to various factors that are orthogonal to the lateralized capture distractor, such as to the fixed manual responses associated to $Task_1$ and $Task_2$[2]. The scalp distribution of the N2pc is similar to previously published N2pc distributions (see Brisson & Jolicœur, 2007b; Hopf et al., 2000; Praamstra, 2006; Robitaille & Jolicœur, 2006).

======= Please insert Figure 2, Figure 3, and Figure 4 about here =======

One sample *t*-tests versus zero revealed that the contralateral positivity in the P1 time-range was present in all Distractor × SOA Conditions (all *ps* < .008). No main effect of Distractor Condition or SOA (both *Fs* < 1), nor Distractor Condition × SOA interaction ($F(1, 23) = 1.55$, $p > .22$) were observed. Given that this positivity was not influenced by our experimental manipulations, as expected given previous research (see Leblanc et al., 2008), we do not consider it further.

Discussion

The primary goal of the present study was to determine whether the involuntary deployment of visual-spatial attention, occurring during the contingent capture of attention, depends on capacity-limited central resources. We incorporated a contingent capture task as the second task of a psychological refractory period (PRP) dual-task paradigm. The first speeded auditory task was used to occupy central resources. The second visual task consisted in identifying a specifically colored digit (T_2) embedded in a search array of heterogeneously colored digits presented on the vertical midline. The visual T_2 array was preceded by a bilateral distractor display comprised of one gray and one colored item. The colored distractor either shared or did not share the target-defining selection feature (i.e., was in the same color as the target or in a nontarget color). Concurrent central load was manipulated by varying the T_1-Distractor display SOA (200 ms or 500 ms). The behavioral results replicated the classical effects of PRP when T_2 is masked (lengthening of response times and diminution of accuracy in $Task_2$ as the T_1-T_2 SOA is decreased) and of contingent attentional capture (lower accuracy in the report of the colored target digit when it is preceded by a peripheral target-colored distractor, but not by a peripheral nontarget-colored distractor). Additionally, no Distractor Condition × SOA interaction was observed on T_2 accuracy. As discussed in the Introduction, the absence of an interaction is inherently ambiguous, in that it could be interpreted as an indication that contingent capture of visual-spatial attention was not affected by SOA or that it was attenuated at the shortest SOA, but that this attenuation was compensated by an opposite effect involving greater difficulty of selecting the item to be consolidated in short-term memory (i.e., the target) under high concurrent central load conditions when an other target-colored item is presented.

To overcome the ambiguity of the behavioral data, we measured the N2pc component of the visual ERP to track directly the allocation of visual-spatial attention after the presentation of the distractor display while participants where performing concurrent central processing known to cause the PRP effect. The electrophysiological results obtained at both SOAs replicated nicely those obtained in Leblanc et al. (2008). That is, target-colored distractors elicited a significant N2pc wave, indicating that visual-spatial attention had been drawn to their location. In contrast, nontarget-colored distractors did not generate N2pc waves, suggesting that participants were able to ignore them and remain focused on the vertical midline, where they knew the central search array containing the second visual target would appear.

It could be argued that because the Distractor display-T2 SOA was fixed at 117 ms, the distractors were temporally predictive of the appearance of the T2 display, and in that sense, that they were task-relevant and not suited to study involuntary capture of attention. Although it is true that the distractors carried an alerting value, it was identical across Distractor conditions, hence it would not have produced differential effects, behavioral or electrophysiological, across conditions. What is more, alerting has been found to be homogeneous across the visual field (Fernandez-Duque & Posner, 1997), so a shift of visual-spatial attention related to alerting would not be expected. Finally, in a similar experimental design using Distractor display-Target SOAs ranging from 117 to 817 ms that eliminated the temporal predictiveness of the distractor display, Leblanc, Prime and Jolicoeur (2008, Experiment 3) replicated the finding of an N2pc in response to target-colored distractors only. Therefore, it is unlikely that contingent capture was observed in the present work because of the temporal predictiveness of the distractors for the appearance of T2. Rather, the N2pc observed in the present study most likely reflects an involuntary shift of visual-spatial attention to the distractor location, contingent on the attentional control settings required to find the target.

Importantly, the N2pc elicited by the target-colored distractor was attenuated when the distractor display was presented in the high concurrent central load condition, that is to say, when it followed T_1 at the short SOA. Given that the N2pc is assumed to reflect the successful deployment of visual-spatial attention to a lateralized item (Brisson & Jolicœur, 2007a, 2007b; Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Eimer, 1996; Hickey et al., 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b; Leblanc et al., 2008; Luck & Hillyard, 1994; Woodman & Luck, 2003), the N2pc attenuation strongly suggests that the allocation of central resources to a concurrent demanding speeded auditory task interfered with the involuntary deployment of visual-spatial attention that occurs during contingent capture. The two SOAs in the present study (200 ms and 500 ms), which were randomly presented from trial to trial, were chosen so that the distractor display would appear well before the response in $Task_1$ (Mean RT_1 over 900 ms), minimizing the possibility of differential task preparation. Therefore, the all-or-none or capacity sharing bottleneck that is postulated to be responsible for the behavioral PRP effect is most probably also responsible for the N2pc attenuation between SOAs in this study.

The attenuation of the N2pc elicited by a lateralized visual item defined by the color has been observed in previous auditory-visual PRP studies (Brisson & Jolicoeur, 2007a, 2007b, 2007c). A fundamental difference between these previous studies and the present one lies in the nature of the N2pc eliciting lateralized visual item. In the previous studies, it was a task-relevant target (i.e., T_2) whereas in the present study it was a task-irrelevant distrator that preceded the central array that contained

T_2. Therefore, contrary to the previous studies in which participants had to deploy visual-spatial attention voluntarily to the location of the N2pc eliciting item in order to maximize performance, here participants had to ignore it to achieve the same goal. The inability to completely ignore the peripheral distractor when it contains a task-defining feature (e.g., target color) has been termed contingent capture, and previous studies have shown that contingent capture has a visual-spatial locus (Leblanc, et al., 2008). Here, we demonstrate for the first time that the involuntary deployment of visual-spatial attention that occurs during contingent capture requires central resources, as does the voluntary deployment of attention.

It is not clear whether the central bottleneck blocked the deployment of spatial attention ***per se***, or whether devoting central resources to T_1 made it more difficult to concurrently maintain the top-down settings for T_2, or whether it was a combination of the above. However, it could be argued tentatively that since the T_2 display was presented only 83 ms and immediately masked, it would be quite difficult, without active control settings, to locate and select T_2 before it was wiped out by the mask. This line of argument suggests that a larger decrement in $Task_2$ accuracy would have been expected at the short SOA if the central bottleneck momentarily disrupted the top-down control settings. It is also possible that the top-down settings were not disrupted during the PRP period, but somehow that the 'pull' of the visual display is blocked while the central bottleneck is occupied. This could be the case if the link between the contents of working memory (in this case, search intentions for the items at fixation) are, somehow, relegated to 'background' while the 'foreground' task of dealing with the tone is most active. Further work will be needed to disentangle these possible explanations. Nonetheless, the present electrophysiological results show convincingly that the involuntary deployment of visual-spatial attention that takes place during contingent capture depends on capacity-limited central attentional mechanisms. Thus, contingent capture of visual-spatial attention is involuntary, in the sense that subjects attempt to maintain their attention at one location (the vertical midline in the present work) but cannot prevent capture by a target-colored distractor. And, perhaps surprisingly, it is not automatic, in the sense that the manifestation of capture depends on the state of central attentional mechanisms.

References

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. ***Perception & Psychophysics***, *55*(5), 485-496.

Brisson, B., & Jolicœur, P. (2007a). Electrophysiological evidence of central interference in the control of visuospatial attention. ***Psychonomic Bulletin & Review***, ***14***, 126-132.

Brisson, B., & Jolicœur, P. (2007b). A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials. ***Psychophysiology***, 44, 323-333.

Brisson, B., & Jolicoeur, P. (2007c) Cross-modal multitasking processing deficits prior to the central bottleneck revealed by event-related potentials. ***Neuropsychologia***, ***45***, 3038-3053.

Dell'Acqua, R., Sessa, P., Jolicœur, P., & Robitaille, N. (2006). Spatial attention freezes during the attention blink. ***Psychophysiology***, 43, 394-400.

Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. ***Psychological Review***, 96, 433-458.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity.

Electroencephalography and clinical Neurophysiology, 99, 225-234.

Fernandez-Duque, D., & Posner, M. I. (1997). Relating the mechanisms of orienting and alerting. ***Neuropsychologia***, *35*(4), 477-486.

Folk, C. L., Leber, A. B., & Egeth, H. E. (2002). Made you blink! Contingent attentional capture produces a spatial blink. ***Perception & Psychophysics, 64***(5), 741-753.

Folk, C. L., & Remington, R. W. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. ***Journal of Experimental Psychology: Human Perception and Performance, 24***(3), 847-858.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. ***Journal of Experimental Psychology: Human Perception and Performance, 20***(2), 317-329.

Green, J.J., Conder, J.A., & McDonald, J.J. (2008). Lateralized frontal activity elicited by attention-directing visual and auditory cues. ***Psychophysiology***, 45, 579-587.

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. ***Journal of Cognitive Neuroscience, 18***(4), 604-613.

Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., Heinze, H. J. (2000). Neural sources of focused attention in visual search. ***Cerebral Cortex***, 10, 1233-1241.

Hopfinger, J. B., & Mangun, G. R. (1998). Reflexive attention modulates processing of visual stimuli in humain extratriate cortex. ***Psychological Science***, 9, 441-447.

Hopfinger, J. B., & Mangun, G. R. (2001). Tracking the influence of reflexive attention on sensory and cognitive processing. ***Cognitive, Affective, and Behavioral Neuroscience, 1***, 56-65.

Johnston, J. C., McCann, R. S., & Remington, R. W. (1995). Chronometric evidence for two types of attention. ***Psychological Science***, 6, 365-369.

Jolicœur, P. (1999). Dual-task interference and visual encoding. ***Journal of Experimental Psychology: Human Perception and Performance***, 25, 596-616.

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

Jolicœur, P., & Dell'Acqua, R. (1999). Attentional and structural constraints on visual encoding. ***Psychological Research/-Psychologische Forschung***, 62, 154-164.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006a). On the control of visual spatial attention. ***Psychological Research***, 70, 414-424.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006b). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. ***European Journal of Cognitive Psychology***, 18, 560-578.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J.B. Long & A.D. Baddeley (Eds.), ***Attention and performance IX***, (pp.187-203). Hillsdale, NJ: Erlbaum.

Kiesel, A., Miller, J., Jolicoeur, P., & Brisson, B. (2008) Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods. *Psychophysiology, 45,* 250-274.

Lamy, D., Leber, A. B., & Egeth, H. E. (2004). Effects of task relevance and stimulus-driven salience in feature-search mode. *Journal of Experimental Psychology: Human Perception and Performance, 30*(6), 1019-1031.

Leblanc, É., & Jolicœur, P. (2005). The time course of the contingent spatial blink. *Canadian Journal of Experimental Psychology, 59*(2), 124-131.

Leblanc, É., Prime, D., & Jolicœur (2008). Tracking the location of visuospatial attention in a contingent capture paradigm. *Journal of Cognitive Neuroscience*, 20, 657-671.

Luck, S.J. (2005). *An introduction to the event-related potential technique*. Cambridge MA: The MIT press.

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.

Luck, S. J., Girelli, M., McDermott, M. T., & 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., Woodman, G. F., & Vogel, E. K. (2000). Event-related potential studies of attention. *Trends in cognitive Sciences*, 4, 432-440.

Mangun, G. R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology*, 32, 4-18.

Mangun, G. R., & Hillyard, S.A. (1991). Modulation of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 1057-1074.

McDonald, J. J., & Ward, L. M. (2000). Involuntary listening aids seeing: evidence from human electrophysiology. *Psychological Science*, 11, 167-171.

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

Müller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of attention: time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 315-330.

Pashler, H. (1991). Shifting visual spatial attention and selecting motor responses: distinct attentional mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 1023-1040.

Pashler, H. (1993). Dual-task interference and elementary mental mechanisms. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence,and cognitive neuroscience* (pp. 245-264). Cambridge, MA: MIT Press.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, 116, 220-244.

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

Praamstra, P. (2006). Prior information of stimulus location: Effects on ERP measures of visual selection and response selection. *Brain Research*, 1072, 153-160.

Praamstra, P., Stegeman, D.F., Horstink, M.W., & Cools, A.R. (1996). Dipole source analysis suggests selective modulation of the supplementary motor area contribution to the readiness potential. *Electroencephalography and Clinical Neurophysiology*, 98, 468-77.

Robitaille, N., & Jolicœur, P. (2006). Fundamental properties of the N2pc as an index of spatial attention: effect of masking. *Canadian Journal of Experimental Psychology*, 60, 101-111.

Serences, J. T., Shomstein, S., Leber, A. B., Golay, X., Egeth, H. E., & Yantis, S. (2005). Coordination of voluntary and stimulus-driven attentional control in human cortex. *Psychological Science, 16*(2), 114-122.

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., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 15-48.

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

Van Selst, M., & Jolicœur, P. (1994). A solution to the effect of sample size on outlier elimination. ***Quaterly Journal of Experimental Psychology: Human Experimental Psychology***, 47A, 631-650.

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.

Footnote

1. For further discussion and empirical evidence validating this theoretical assumption, see Brisson and Jolicœur (2007a, 2007b).

2. The mapping procedure used here is similar to the anti-symmetric procedure (Praamstra, Stegeman, Horstink, & Cools, 1996), which has also been used to characterise the scalp distributions of the N2pc (Praamstra, 2006) and other lateralized components, such as the lateralized readiness potential (LRP: Praamstra, Stegeman, Horstink, & Cools, 1996) and the anterior directing attention negativity (ADAN: Green, Conder, & McDonald, 2008). Both procedures yield symmetric maps, but instead of having foci of the same polarity in the two cerebral hemispheres as here, with the anti-symmetric procedure, the voltage polarity is arbitrarily reversed in one hemisphere, rendering both hemisphere opposite in polarity.

Acknowledgments

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chairs Program, and the Université de Montréal awarded to PJ and by NSERC postgraduate scholarships awarded to BB and ÉL.

Table 1: Mean Accuracy (percent correct) and RT (ms) to T_1 and T_2 for Each SOA Condition × Distractor Condition.

SOA Condition	Distractor Condition	RT_1	ACC_1	RT_2	ACC_2
200 ms	Target-color	921 (71)	83 (2.0)	1106 (71)	76 (3.4)
	Nontarget-color	915 (68)	84 (1.7)	1099 (71)	82 (2.7)
	Distractor-absent	922 (67)	84 (1.8)	1118 (70)	81 (2.7)
500 ms	Target-color	982 (73)	84 (1.8)	936 (64)	78 (3.4)
	Nontarget-color	993 (76)	85 (1.7)	945 (73)	83 (2.7)
	Distractor-absent	1001 (74)	86 (1.7)	945 (70)	81 (2.3)

RT_1 = reaction time in $Task_1$; RT_2 = reaction time in $Task_2$.

ACC_1 = accuracy for $Task_1$; ACC_2 = accuracy for $Task_2$

Standard error of the mean in parentheses.

Figures Captions

Figure 1: Illustration of the sequence of events in each trial. Two separate speeded responses were required on each trial. The first response was to the pitch of the tone (T_1) and the second response was to the identity of the pre-specified target-colored digit in the visual (T_2) target display. All colors and gray were equiluminant to equate low sensory activity.

Figure 2: Grand-average event-related potential (ERP) waveforms time-locked to the distractor display onset at ipsilateral and contralateral PO7/PO8 electrode sites for all SOA × Distractor Conditions. In this and all subsequent figures, a 15 Hz low-pass filter was applied after analysis for display purposes only.

Figure 3: Contralateral minus ipsilateral difference waves time-locked to the distractor display onset at PO7/PO8 for all SOA × Distractor Conditions.

Figure 4: Scalp distribution of the electrical potentials measured during the N2pc (200-250 ms) post-distractor display onset time windows for both SOAs in the Target-color Distractor Condition, as well as the N2pc effect, computed from the 500 ms SOA minus 200 ms SOA N2pc difference waves. The scalp distributions were calculated on the basis of the contralateral minus ipsilateral difference waves used to calculate the N2pc, and are thus symmetrical about the midline.

Figure 1

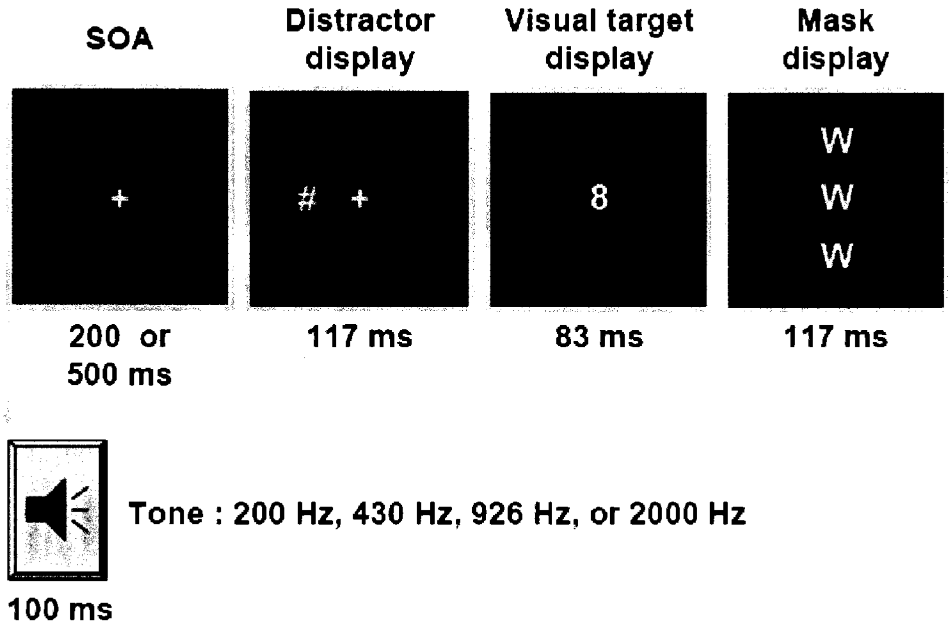
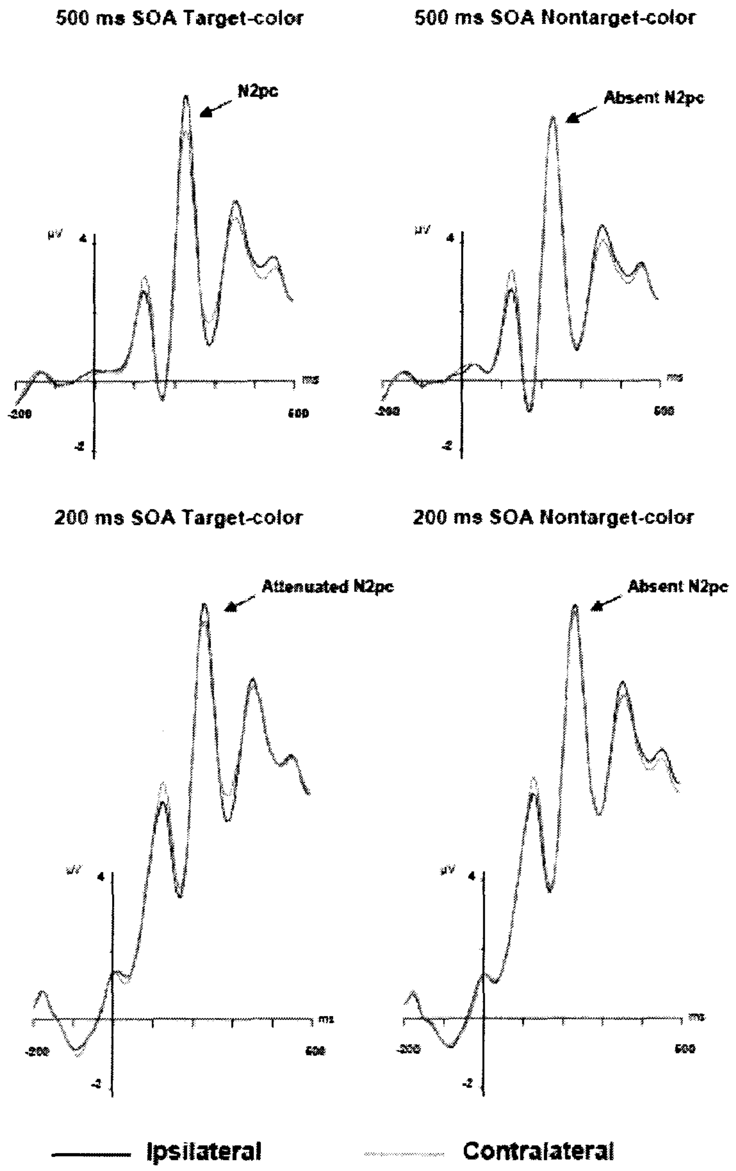

SOA
Distractor display
Visual target display
Mask display
+
+
8
W
W
W
200 or 500 ms
117 ms
83 ms
117 ms
Tone : 200 Hz, 430 Hz, 926 Hz, or 2000 Hz
100 ms

Figure 2



500 ms SOA Target-color

500 ms SOA Nontarget-color

200 ms SOA Target-color

200 ms SOA Nontarget-color

Figure 3

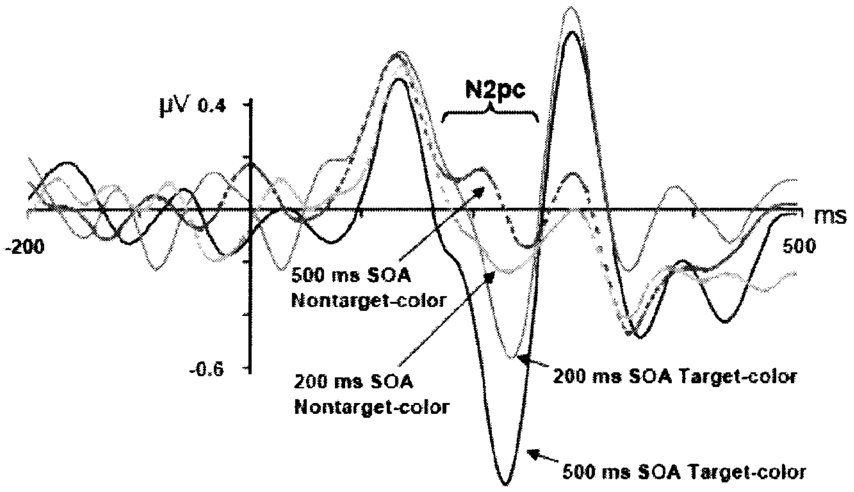
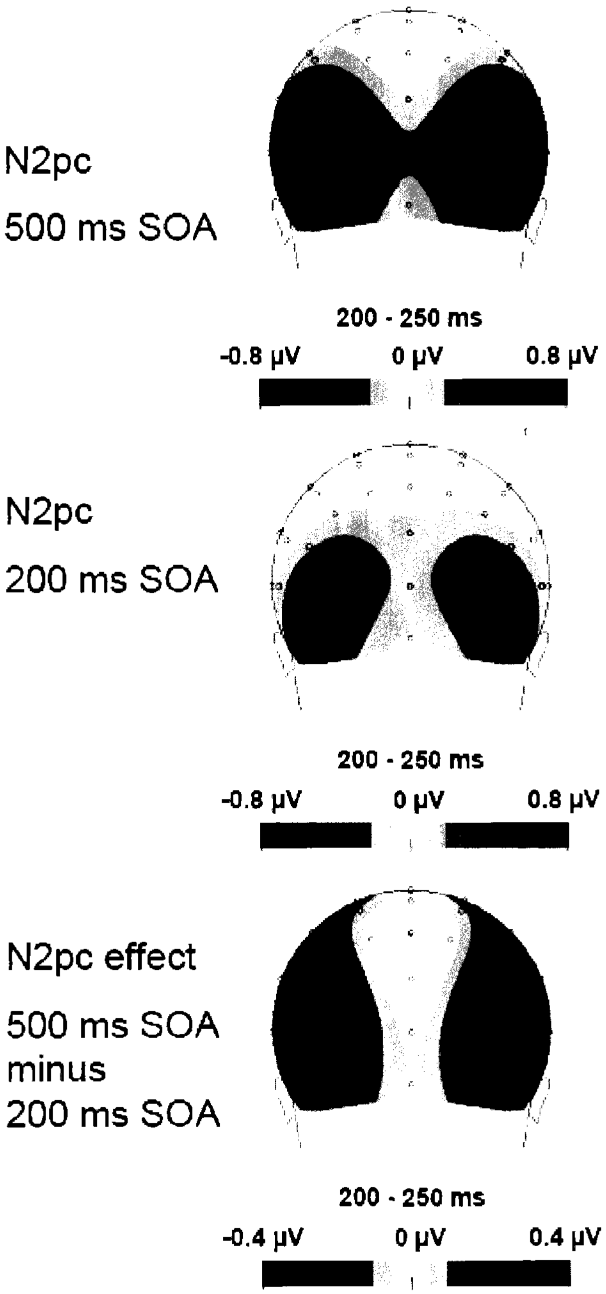

µV 0.4
-0.6
-200
500
ms
N2pc
500 ms SOA Nontarget-color
200 ms SOA Nontarget-color
200 ms SOA Target-color
500 ms SOA Target-color

Figure 4



N2pc

500 ms SOA

N2pc

200 ms SOA

N2pc effect

500 ms SOA
minus
200 ms SOA

Article #4: Cross-modal multitasking processing deficits prior to the central bottleneck revealed by event-related potentials

Cross-modal multitasking processing deficits prior to the central bottleneck revealed by event-related potentials

Benoit Brisson and Pierre Jolicœur

Centre de recherche en Neuropsychologie et Cognition, Université de Montréal, Montréal, Qc

Article published in *Neuropsychologia* (2007), 45: 3038—3053.

Abstract

We investigated whether concurrent processing of a tone (T_1) interferes with early sensory-perceptual processing of a visual target (T_2) in variants of the psychological refractory period paradigm using the event-related potential (ERP) method and 70-channel electroencephalographic recordings. T_1, which required a speeded response, was presented in all trials. In half of the trials, T_1 was followed by a bilateral visual display, T_2, which also required a speeded response. A single T_1-T_2 stimulus onset asynchrony was adjusted dynamically to maximize task overlap in a hard-$Task_1$ condition while minimizing task overlap in an easy-$Task_1$ condition. The ERP to T_1 in trials with only T_1 presented (uncontaminated by T_2) enabled us to subtract T_1-related activity from the dual-task T_2-locked ERPs. An attenuation of the T_2-locked occipital N1 was observed in the hard-$Task_1$ condition, relative to the easy-$Task_1$ condition, both when T_2 required a discriminative response and a detection response. An attenuation of the visual P1 component was also observed when T_2 required a discriminative response. The N2pc was also attenuated, and the sustained posterior contralateral negativity (SPCN) was delayed, by concurrent processing in the discrimination task. Implications for models of dual-task interference are discussed.

KEYWORDS: Cross-modal PRP paradigm, dual-task interference, event-related potentials, visual P1, occipital N1, N2pc, SPCN, human electrophysiology

Introduction

The limitations in performing two concurrent tasks have been extensively studied using the psychological refractory period (PRP) paradigm. In the PRP paradigm, two distinct targets, T_1 and T_2, are presented sequentially, and a speeded response is required for each target. The overlap between T_1 and T_2 processing (i.e., between $Task_1$ and $Task_2$) is typically manipulated by varying the temporal interval between the onsets of the two targets (i.e., the T_1-T_2 stimulus onset asynchrony, or SOA). Even with very simple stimuli and associated tasks, the PRP paradigm yields robust interference effects, reflected principally by an increase in mean response time to the second target (RT_2) as SOA is reduced (i.e., as task overlap is increased; see Pashler, 1994, for a review).

Several researchers have proposed that the lengthening of RT_2 (i.e., the PRP effect) is caused by a central processing bottleneck at a late stage of categorization and/or response selection and decision making (e.g., McCann & Johnston, 1992; Pashler & Johnston, 1989; Pashler, 1994; Welford, 1952). Specifically, the central bottleneck model postulates that central processes such as response selection and decision making cannot operate concurrently on more than one target. Therefore, under high task overlap conditions, response selection to T_2 is postponed until central mechanisms are free from selecting the response to T_1. This postponement leads to a longer waiting period as task overlap increases, which would explain the lengthening of RT_2 as SOA is decreased in classical PRP paradigms. Importantly, proponents of this type of model also usually assume that, under appropriate conditions (e.g., when sensory modalities are not overloaded and when responses do not require the same output modality), early sensory-perceptual processes that lead to stimulus identification (and response execution processes that lead to the overt response) can operate in both tasks in parallel, without interference, and can proceed simultaneously with the central bottleneck stage(s).

Several aspects of the central bottleneck model have been challenged. For example, it has been proposed by some that the bottleneck is strategic in nature (and so should be eliminated under appropriate conditions; see Meyer & Kieras, 1997), while others have demonstrated that a class of central capacity sharing models (e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2003) predicts all the hallmark effects of the central bottleneck model, and therefore are viable alternatives to the central all-or-none bottleneck model. However, the relatively late, central locus of interference in the PRP paradigm is accepted by virtually all researchers and incorporated into most models of dual-task interference.

The most convincing behavioral evidence in favour of a late, central locus of interference has been obtained with the locus-of-slack method (McCann & Johnston, 1992; Pashler & Johnston, 1989; Schweickert, 1980). This chronometric method consists of manipulating the difficulty (i.e., duration) of specific stages of T_2 processing, and observing the interaction of this manipulation with SOA. If the stage that was affected by the manipulation is at or after the bottleneck, then additive effects of the manipulation and SOA are predicted. That is, the effects of the Task_2 manipulation will be equal at short and long SOAs. However, if the stage that was influenced by the manipulation is before the bottleneck, then an underadditive effect of the Task_2 manipulation with decreasing SOA is predicted. That is, the effect of the manipulation in Task_2 is predicted to decrease as SOA is reduced, and even to disappear at very short SOAs. Whereas additive effects have been observed when factors that are argued to influence response selection were manipulated, such as stimulus repetition (Pashler & Johnston, 1989) and response compatibility (McCann & Johnston, 1992), underadditive effects have been observed when stimulus intensity (e.g., Pashler, 1984; Pashler & Johnston, 1989; Oriet & Jolicœur, 2003) and stimulus clarity (i.e., intact vs. distorted letters; Johnston, McCann, & Remington, 1995) have been manipulated.

Several electrophysiological studies have also corroborated a central locus of interference in the PRP paradigm. Osman and Moore (1993), for example, demonstrated that the latency of the T_2-locked lateralised readiness potential (LRP) was increasingly delayed as SOA decreased, in the same manner as RT_2. Moreover, the T_2-locked LRP sometimes preceded the response in Task_1, suggesting that response selection for T_2 could sometimes be completed prior to response execution in Task_1. Combined, these results suggest that the locus of the PRP effect occurs at or before response selection. Results of a subsequent PRP study which also focused on the LRP (Sommer, Leuthold, & Schubert, 2001) pointed to the same conclusion. For his part, Luck (1998) examined earlier ERP components, including the P3 component, which is often thought to be an index of updating in short-term memory (Donchin, 1981; but see Verleger, 1988). In this study, a visual-visual PRP paradigm was used in which both T_1 and T_2 were presented at fixation, and SOAs were 50 ms, 150 ms, or 350 ms. Capitalizing on the well known fact that the P3 component is larger for infrequent task-defined target categories than for frequent task-defined target categories, Luck (1998) isolated the frequency-related P3 component from other frequency-insensitive activity, including overlapping $Task_1$ activity, by subtracting the ERP for frequent-T_2 category stimuli trials from the ERP for infrequent-T_2 category stimulus trials. The amplitude of the T_2-locked P3 component was significantly smaller in short SOA trials (50 ms SOA) than in long SOA trials (350 ms SOA). Although the effect on P3 latency was only 51 ms, compared to the 220 ms effect on RT_2, it was also significant. However, neither the amplitude nor the latency of the P2 component, which often precedes the P3 in the infrequent minus frequent difference waveform, were significantly modulated by SOA. Because it logically ensues that task defined target category frequency-related components can not be elicited before the task-defined category has been identified, the P2 results in this study suggest that, in agreement with prominent models of dual-task interference, early sensory-perceptual processes that lead to target identification and categorization could operate without significant interference from concurrent processing in $Task_1$, although the modulation of the P3 component may indicate that some interference can occur prior to response selection.

Recently however, Dell'Acqua, Jolicœur, Vespignani, & Toffanin (2005) observed SOA effects on P2 amplitude and on both P2 and P3 latency in a study that was very similar to Luck (1998), but in which a different range of SOAs was used (SOAs of 100 ms, 350 ms, or 800 ms). Moreover, P3 latency effects were positively correlated with the PRP effect across subjects for whom a clear P3 was elicited. These results were interpreted as evidence in favour of the central interference theory (Jolicœur, 1998, 1999a, 1999b), which postulates that short-term consolidation (reflected by the P3 component) and response selection (postulated to be an important locus of the PRP effect) share common limited central resources. However, these results also suggest that interference may begin to occur before stimulus identification or classification (i.e., at a perceptual level of processing). Using fMRI, Jiang and Kanwisher (2003) have demonstrated strong overlap between brain regions engaged in response selection and those engaged in perceptual discrimination, which provides convergent support for possible early perceptual interference in the PRP paradigm, at least when difficult perceptual discriminations are involved.

The primary goal of the present study was to investigate more directly whether concurrent processing of a first target (T_1) interferes with early sensory-perceptual processing of a second target (T_2) in a cross-modal PRP paradigm, by focusing on the visual (occipital) P1 and N1 components elicited by a visual T_2 in different overlapping auditory $Task_1$ conditions.

Experiment 1

In this experiment, T_1 was a tone and participants were required to make a speeded 4-alternative discriminative choice response (by button press) to indicate the pitch of T_1 (200, 430, 926, or 2000 Hz). It has been demonstrated that when four tone frequencies arrayed from low to high are mapped to four response keys arrayed from left to right, the mean response times to the highest and lowest frequencies are shorter then those of the middle frequencies, and that this difficulty effect, when manipulated in $Task_1$, delays the onset of processing in $Task_2$ at the same central bottleneck stage as when SOA is manipulated (see Jolicœur, 1999a; Jolicœur, Dell'Acqua, & Crebolder, 2000; Van Selst & Johnston, 1996). Taking advantage of this built-in manipulation of $Task_1$ difficulty, the T_1-T_2 stimulus onset asynchrony (SOA) was adjusted dynamically so that T_2 would be presented usually after the response to T_1 when the tone had the lowest or highest frequency (easy-$Task_1$ condition), but before the response to T_1 when the tone had one of the middle frequencies (hard-$Task_1$ condition). This enabled us to vary task overlap randomly (which was maximized in the hard-$Task_1$ condition and minimized in the easy-$Task_1$ condition) while using identical SOAs in both $Task_1$ conditions.

Because $Task_1$ interference on T_2 processing was the primary focus in this study, it was crucial to remove overlapping $Task_1$ activity from the

T_2-locked ERP waveform of interest, especially given that our $Task_1$ difficulty manipulation was designed to affect response times to T_1 (and as a consequence, $Task_1$ overlap associated, amongst other things, to $Task_1$ response preparation and execution processes). To remove such overlapping activity, we included single-$Task_1$ trials in which only T_1 was presented. These single-$Task_1$ trials, randomly intermixed with dual-task trials, were identical to the dual-task trials, except that T_2 was not presented and therefore no associated $Task_2$ was required. By computing the average EEG activity time-locked to T_1 onset + SOA (the time at which T_2 would have been presented) in these trials, we were able to estimate overlapping $Task_1$ activity, which we then subtracted from the T_2-locked (i.e., T_1 onset + SOA) dual-task ERPs, thus isolating the ERP associated to T_2 processing. Similar subtraction procedures have been used in a number of experiments designed to isolate a specific ERP in situations involving overlapping ERPs (e.g., Luck, 1998; Luck, Fan, & Hillyard, 1993; Vogel, Luck, & Shapiro, 1998).

According to most models of dual-task interference, T_1-only trials (in the context of dual-task trials) engage the same processing mechanisms associated with T_1 processing in dual-task trials. Thus, our subtraction procedure should reveal the ERP related to T_2, in dual-task trials, uncontaminated by the ERPs reflecting the processing of T_1. If our subtraction procedure is valid and if the occipital P1 and/or N1 in the subtraction waveforms are attenuated in the hard-$Task_1$ condition relative to the easy-$Task_1$ condition, it would provide strong electrophysiological evidence that central processing of a tone interferes with concurrent early sensory-perceptual processing of a visual target.

Previous studies (Brisson & Jolicœur, 2007a, 2007b) have demonstrated that a demanding concurrent speeded auditory task attenuated the N2pc (N2 ***posterior contralateral*** : Eimer, 1996; Luck & Hillyard, 1994; Luck, Girelli, McDermott, & Ford, 1997; Woodman & Luck, 2003) and delayed the onset of the sustained posterior contralateral negativity (SPCN: Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b; Klaver, Talsma, Wijers, Heinze, & Mulder, 1999; McCollough, Machizawa, &Vogel, 2007; Vogel & Machizawa, 2004). Both the N2pc and the SPCN are thought to index visual activity, because they arise at electrode sites contralateral to the to-be-processed visual item(s), which link the activity to the location of the task relevant item(s) in the visual field, and have a posterior scalp distribution, which is consistent with activity in the extrastriate visual cortex (McCollough et al., 2007). However, they are thought to index different specific processes. On one hand, the N2pc, which typically starts at about 180 ms post-target onset and lasts about 100 ms, is thought to be a valid index of covert visual-spatial attention in light of several results reviewed by Woodman and Luck (2003). On the other hand, the SPCN, which typically starts at about 300 ms post-target onset, is thought to reflect visual short-term memory (VSTM) activity. Indeed, it has been shown that the amplitude of the SPCN increases as the number of to-be-remembered items in the visual display increases, but only up to the participants VSTM capacity, and that it is a sustained response throughout the retention period (McCollough et al., 2007; Vogel & Machizawa, 2004). Furthermore, it has been found that the SPCN duration was correlated with RT in tasks that required a speeded response (Robitaille & Jolicœur, 2006). It was argued that the conditions that produced the longer RT most likely required the participants to maintain the visual trace in VSTM for a longer period, and therefore that the time course of the SPCN tracks the duration the visual trace must be held in VSTM (Prime, Chénier, & Jolicœur, 2006).

The present design also enabled us to determine whether the attenuation of the N2pc and delay of the SPCN onset latency in high concurrent central load conditions observed in Brisson and Jolicœur (2007a, 2007b) could be replicated with the present manipulation of Task_1 demand. Central load effects on the P3 component could also be examined here.

Methods

Participants

Twenty-eight undergraduate students at the Université de Montréal participated in this experiment for financial compensation. Four participants were excluded for reasons outlined below, leaving 24 participants (13 women), aged 18-31 (mean age: 22 years) in the final sample. All participants were neurologically intact and reported having normal hearing and normal or corrected-to-normal visual acuity and color vision. Written consent was obtained from each participant at the beginning of the experiment. The procedure was vetted by the appropriate ethics committee at the Université de Montréal.

Stimuli and Procedure

Participants sat in a dimly lit, electrically shielded room, facing a computer screen, at a viewing distance of 57 cm. A 100 ms tone (T_1), emitted simultaneously by two loudspeakers that were placed on each side of the computer screen, was presented on each trial. T_1 could be at one of four frequencies: 200 Hz (68 dB), 430 Hz (60 dB), 926 Hz (60 dB), or 2000 Hz (56 dB). All four frequencies were randomly presented in each block. On half of the trials, a 50 ms visual display was presented on the computer screen (see Figure 1a), shortly after the tone. The visual display contained one red ($x = .382$, $y = .275$; CIE (x, y) chromaticity coordinates (Wyszecki & Stiles, 1982)) and one green ($x = .277$, $y = .506$) square, each with a gap in one side (different for each square). Both squares subtended a visual angle of $1° \times 1°$ and the gaps were 0.33°, as illustrated in Figure 1. Both colors were equiluminant (26.3 cd/m^2) to equate low sensory responses and were presented on a dark-grey background (0.25 cd/m^2). One square was presented in the right visual hemifield and the other was presented in the left visual hemifield. The centre of the squares was 1.5° below, and 3.5° to the left or right of a fixation point that remained at the centre of the computer screen for the duration of the trial. The red square was the visual target (T_2) for half of the participants and the green square was T_2 for the other half. T_2 appeared randomly on the left or right of fixation.

========== Please insert Figure 1 about here ==========

After the presentation of the written instructions, each tone was presented, in sequence arranged from low to high frequency, five times, for familiarisation. Participants then performed one practice block of 64 trials (16 single-Task$_1$ trials, 16 single-Task$_2$ trials, and 32 dual-task trials) followed by 16 experimental blocks of 64 trials. The sole purpose of the first experimental block was to calculate the SOA that was used in the subsequent block (see SOA calculation below), and therefore was excluded from the behavioral and electrophysiological analyses.

Each trial was initiated by pressing the "N" and "V" keys simultaneously with the right and left index fingers respectively. 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. Five hundred milliseconds later, the tone (T_1) was presented and a 4-choice speeded response to the pitch of the tone was required (responses to T_1 were made with fingers of the right hand: response keys where "N," "M," "," and "." for the 200, 430, 926, and 2000 Hz tones respectively).

Half of the experimental trials were dual-task trials and half were single-Task$_1$ trials. In dual-task trials, T_1 was followed by a 50 ms bilateral visual display that contained T_2 (see Figure 1) and a 4-choice speeded response to the location of the gap in T_2 (left, bottom, up, or right) was required (responses to T_2 were made with the fingers of the left hand: response keys were “Z,” “X,” “C,” and “V” for left, bottom, up, and right gaps respectively). Instructions emphasized the importance to respond as quickly and accurately as possible to T_1, as soon as T_1 was presented, and then to respond as quickly and accurately as possible to T_2, when T_2 was presented. In single-Task_1 trials, a 50 ms stimulus-free interval replaced the visual display and no overt response was required for the absent T_2 (see Figure 1). Dual-task and single-Task_1 trials were randomly intermixed in each block. Therefore, 32 dual-task trials (16 easy-Task_1 and 16 hard-Task_1 trials) and 32 single-Task_1 (16 easy-Task_1 and 16 hard-Task_1 trials) occurred in each experimental block. After exclusion of the practice and SOA calibration blocks, this amounted to 480 dual-task trials (240 easy-Task_1 and 240 hard-Task_1 trials) and 480 single-Task_1 (240 easy-Task_1 and 240 hard-Task_1 trials).

The T_1-T_2 SOA was identical for the easy- and hard-Task_1 condition and was calculated from block to block as the mean response time to T_1 in the preceding block, both conditions combined.

Trials ended with the simultaneous disappearance of the fixation point and appearance of the visual feedback between 1250 ms and 1750 after response to T_2 in dual-task trials or 5000 ms after trial initiation in single-Task_1 trials. 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 fixation point a “+” or “-” indicated a correct or incorrect response to T_2, respectively (all responses to T_2 in single-Task$_1$ trials were followed by a "-" and absence of a response to T$_2$ was followed by a "+"). Participants were instructed to maintain central eye fixation throughout the trial and blink only when the feedback was on the screen.

EEG Recording and Analysis

The EEG was recorded from 64 active Ag/AgCl electrodes (BioSemi ActiveTwo system) mounted on an elastic cap and referenced to the average of the left and right mastoids. Electrodes were placed according to the extended International 10/20 system at Fp1, Fpz, Fp2, 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. A lowpass filter of 40 Hz was applied and the EEG and EOG signals, digitized at 256 Hz, were averaged offline.

Trials with eye blinks (VEOG > 80 µV), large horizontal eye movements (HEOG > 30 µV), and/or artefacts at electrode sites of interest (i.e., > 80 µV at PO7, PO8 and/or POz electode sites) were rejected. Four participants were excluded because less than 144 trials (i.e., less than 60% of trials) remained after trial rejection in at least one of the four condition (easy- and hard-$Task_1$ condition) × trial type (single-$Task_1$ and dual-task) cells. Of the remaining 24 participants, an average of 91% of easy-$Task_1$ trials (90% of single-$Task_1$ trials and 91% of dual-task trials), and 92% of hard-$Task_1$ trials (92% of single-$Task_1$ trials and 92% of dual-task trials) remained after trial rejection. None of these participants had residual eye movements that deviated more then 0.2° (i.e., average HEOG > 3.2 µV) towards T_2 after rejection criteria was applied (see Luck, 2005).

Separate ERP waveforms were computed for dual-task and single-$Task_1$ trials, for each $Task_1$ condition. For the dual-task trials, the EEG was averaged starting 200 ms prior to T_2 onset (i.e., T_1 onset + SOA) and ending 500 ms post-T_2 onset, and baseline corrected based on the 200 ms pre-T_2 period. For the single-$Task_1$ trials, the EEG was averaged according to when T_2 would have appeared (i.e., T_1 onset + SOA). These single-$Task_1$ ERPs where subtracted from the T_2-locked dual-task ERPs to eliminate overlapping activity of $Task_1$ from the T_2 elicited activity. The mean amplitude measurements of the occipital P1 and N1 (mean amplitude during the 100-120 ms and 150-190 ms post visual-display time interval for the occipital P1 and occipital N1 at PO7/PO8 electrode sites), and of the P3 (mean amplitude during the 300-400 ms post visual-display time interval at the POz electrode site) were estimated based on these dual-task minus single-$Task_1$ difference waves.

The N2pc and SPCN were quantified following the subtraction of the ipsilateral waveforms (average of left-sided electrode with left visual field target and right-sided electrode with right visual field target) from the contralateral waveforms (average of left-sided electrode with right visual-field target and right-sided electrode with left visual-field target). This subtraction eliminates overlapping activity that was not lateralized with respect to the side of T_2 (e.g., $Task_1$ activity). Therefore, the N2pc and SPCN subtraction waveforms were based on the T_2 locked dual-task ERPs only. N2pc measurements (mean amplitude during the 200-260 ms post-visual display time window) and SPCN measurements (mean amplitude during the 320-400 ms and 450-500 ms post-visual display time window) were obtained from the contralateral minus ipsilateral difference waveforms at PO7/PO8 electrode sites, were the N2pc and SPCN were maximal.

N2pc, SPCN, and P3 onset latency measurements were also calculated and analysed using a jackknife method (Kiesel, Miller, Jolicœur, & Brisson, 2007; Miller, Patterson, Ulrich, 1998; Ulrich & Miller, 2001). With the jackknife method, n grand average waveforms are computed with n-1 participants (a different participant is removed for each 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 must be adjusted according to

$$F_{ajusted} = F / (n-1)^2$$

(see Ulrich & Miller, 2001 for a general proof of this adjustment).

Behavioral data (i.e., mean reaction time and percent accurate response to T_1 and T_2) and electrophysiological data were submitted to an analysis of variance (ANOVA), in which $Task_1$ condition (easy vs. hard) was treated as a within-subject factor. Trial type (single-$Task_1$ trials vs. dual-task trials) was included as an additional within-subject factor in the analysis performed on accuracy and mean reaction time to T_1, and laterality of T_2 in respect to electrode site (i.e., ipsilateral vs. contralateral) was included as an additional within-subject factor in the analysis performed on the occipital N1 data.

Results

Behavioral results

Only trials with correct responses to both T_1 and T_2 were included in the reaction time (RT) analyses, and outliers were excluded using the method described in Van Selts and Jolicœur (1994). Single- $Task_1$ and dual-task trial accuracy and mean RTs for T_1, and dual-task trial accuracy and mean RTs for T_2 in each $Task_1$ condition are shown in Table 1, as well as mean SOA. As expected, mean RT_1 was significantly longer, $F(1, 23) = 190.2, p < .0001$, and T_1 accuracy was significantly lower, $F(1, 23) = 84.3, p < .0001$, in the hard-$Task_1$ condition than in the easy-$Task_1$ condition. Accuracy to T_1 was identical for single-$Task_1$ trials and dual-task trials ($F < 1$) and there was no $Task_1$ condition × trial type interaction ($F < 1$). The mean RT_1 differences in single-$Task_1$ trials and dual-task trials in the hard-$Task_1$

condition (23.5 ms) and in the easy-Task$_1$ condition (0.3 ms) were small. Nevertheless, mean RT$_1$ was significantly longer in single-Task$_1$ trials than in dual-task trials, $F(1, 23) = 5.4$, $p < .03$, and the Task$_1$ condition × trial type interaction was marginally significant, $F(1, 23) = 3.8$, $p < .07$.

Importantly, even though the visual task (Task$_2$) was identical in each Task$_1$ condition, RT to T$_2$ was about 70 ms longer in the hard-Task$_1$ condition than in the easy-Task$_1$ condition, $F(1, 23) = 56.0$, $p < .0001$. Thus, a carry-forward effect of Task$_1$ difficulty on Task$_2$ was observed, demonstrating that, as expected, our Task$_1$ manipulation affected a stage of processing that occurred at or before the central bottleneck. Furthermore, although not a large effect, responses to T$_2$ were significantly less accurate in the hard-Task$_1$ condition than in the easy-Task$_1$ condition, $F(1, 23) = 8.0$, $p < .01$.

========== Please insert Table 1 about here ==========

Electrophysiological results

Occipital P1 and N1

Grand-average waveforms locked to T$_2$ onset (i.e., T$_1$ + SOA) are shown in Figure 2 as a function of Task$_1$ condition, trial type, and laterality of T$_2$ at PO7/PO8 electrode sites. The dual-task minus single-Task$_1$ difference waves for both Task$_1$ conditions in function of laterality are shown in Figure 3. Note that the subtraction procedure flattened the pre-T$_2$ baseline, indicating that it was effective in removing systematic Task$_1$

overlap from the T_2-locked visual ERPs. The analyses revealed that although both the visual display and $Task_2$ were identical in both $Task_1$ conditions, the amplitude of the occipital P1 was smaller in the hard-$Task_1$ condition (mean amplitude = -0.43 μV) than in the easy-$Task_1$ condition (mean amplitude = 0.9 μV; F (1, 23) = 6.5, $p < .02$). No significant effect of laterality, $F(1, 23) = 1.86$, $p > .18$, nor $Task_1$ condition × laterality interaction ($F < 1$) was observed. It is important to acknowledge that the greater acceleration in mean RT_1 (shorter RT_1) in dual-task trial compared to single-$Task_1$ trials in the hard-$Task_1$ condition (23.5 ms) than in the easy-$Task_1$ condition (0.3 ms) could potentially have created the observed P1 effect. Indeed, an acceleration in mean RT_1 should be reflected in a leftward shift of $Task_1$ related ERP activity. Because $Task_1$ related activity is a low frequency, negative deflecting wave (see single-$Task_1$ ERPs in Figure 2), a leftward shift should result in a greater $Task_1$ related negativity in the P1 time window than what was estimated by computing the single-$Task_1$ trial ERPs. To evaluate whether this could have influenced the observed P1 result, we shifted the single-$Task_1$ ERPs by the difference in trial type mean RT_1 in both $Task_1$ conditions before performing the subtraction. After correction, there was still a marginally significant $Task_1$ difficulty effect on the P1 amplitude ($F(1, 23) = 4.0$, $p < .06$), suggesting that the P1 effect was not artificially created by the subtraction procedure.

The amplitude of the occipital N1 was also substantially smaller in the hard-$Task_1$ condition (mean amplitude = -3.76 μV) than in the easy-

Task_1 condition (mean amplitude = -4.73 μV), $F(1, 23) = 11.04$, $p < .003$. Contrary to what was observed in the P1 time range, there was a significant effect of laterality in the occipital N1 time range (ipsilateral vs. contralateral), $F(1, 23) = 7.04$, $p < .02$, revealing a larger N1 contralateral to T_2. No Task_1 condition × laterality interaction was observed, $F(1, 23) = 1.54$, $p > .22$. Note that it was not necessary, here, to shift single-Task_1 ERPs to correct for the differences in mean RT_1 between trial types, because the correction would only have accentuated the Task_1 difficulty effect on the occipital N1 amplitude.

Subsequent analyses revealed that both the Task_1 difficulty and laterality effects were present both in the 150-170 ms, $F(1, 23) = 5.26$, $p < .031$, and $F(1, 23) = 4.86$, $p < .04$, for the Task_1 difficulty and laterality effects, respectively, and 170-190 ms post-T_2 time window, $F(1, 23) = 15.44$, $p < .001$, and $F(1, 23) = 5.023$, $p < .035$, for the Task_1 difficulty and the laterality effects, respectively.

Figure 4 shows current source density (CSD; Pernier, Perrin, & Bertrand, 1988) maps computed from the average voltage of the dual-task minus single-Task_1 corrected waveforms in the 100-120 ms (visual P1; left panels) and in the 150-190 ms (occipital N1; right panels) post-T_2 onset time window for the easy- and hard-Task_1 conditions (top and middle maps, respectively). The bottom CSD maps in Figure 3 shows the easy-Task_1 minus hard-Task_1 difference map. The data were rearranged such that the left electrodes in the figure represent the electrodes contralateral to T_2 and the right electrodes represent the electrodes ipsilateral to T_2. These results highlight several important aspects of the results. Firstly, the CSD scalp distribution of the visual P1 and N1 effects are clearly very posterior and have a tight focus. Although neural generators of ERPs are not necessarily located directly beneath the locus of maximal voltage, the transformation of voltage maps into current source density in the maps shown in Figure 3 emphasizes nearby, superficial, radial neural generators (Pernier et al., 1998). Thus, the sharp foci in the maps in Figure 3 are consistent with a neural generator in extra-striate visual cortex, as would be expected for the visual P1 and N1 components.

======= Please insert Figure 2, Figure 3 and Figure 4 about here =======

N2pc and Sustained posterior contralateral negativity (SPCN)

Contralateral minus ipsilateral difference waveforms are presented in Figure 5 as a function of $Task_1$ condition at PO7/PO8 electrode sites, where the N2pc and SPCN were maximal. A significant effect of $Task_1$ difficulty was observed on the N2pc mean amplitude, $F(1, 23) = 5.44$; $p < .03$. To evaluate whether the amplitude effect was caused by an increase in the N2pc onset latency, an additional 15 Hz low-pass filter was applied to the subtracted waveforms and the time at which the waveform reached -0.3 μV, starting at 150 ms post-visual display, was measured and then analysed using the jackknife method. The jackknife analysis revealed no effect on N2pc onset latency ($F < 1$).

The SPCN is the second negative deflection in the contralateral minus ipsilateral difference waveforms (see Figure 5). The SPCN mean amplitude in the 320-400 ms post-visual display time window was attenuated in the hard-Task$_1$ condition, $F(1, 23) = 8.74$; $p < .007$. A jackknife analysis based on the time at which the 15 Hz low-pass filtered waveform reached -0.75 µV, starting at 300 ms post-visual display, revealed a significant 50 ms effect of Task$_1$ difficulty on SPCN latency, $F(1, 23) = 5.76$; $p < .025$. When analysing the SPCN mean amplitude in the later 450-500 ms post-visual display time window, no main effect of Task$_1$ difficulty ($F < 1$) was observed, suggesting that a stable visual short-term memory representation was eventually established in both Task$_1$ condition (which is corroborated by the fact that T$_2$ accuracy did not differ across these conditions).

========== Please insert Figure 5 about here ==========

P3 component

As can be seen in Figure 6, the amplitude of the P3 component, which was maximal at POz and corresponded with the usual bilateral centro-parietal distribution, was substantially smaller in the hard-Task$_1$ condition (mean amplitude = 9.3 µV) than in the easy-Task$_1$ condition (mean amplitude = 11.6 µV, $F(1, 23) = 31.2$, $p < .001$). A jackknife analysis based on the time at which the waveform reached 7.5 µV, starting at 250 ms post-visual display revealed that the 13 ms delay in the hard-Task$_1$ condition was not significant ($F < 1$).

========== Please insert Figure 6 about here ==========

Discussion

Several important results were obtained in Experiment 1. The most important discovery concerns the modulation of the amplitude of the occipital P1 and N1 by central attentional load. The occipital P1 and N1 elicited by identical visual displays associated with identical tasks were smaller when task overlap was maximized (hard-Task$_1$ condition) than when task overlap was minimized (easy-Task$_1$ condition). The latency of the components and scalp distribution of the voltage map suggested that the P1 and N1 components we observed originated in occipital cortex. This supposition was supported by the sharply focused scalp distributions of the current source density analyses based on the mean voltage in a time window centered on the latency of the peak of the visual P1 (100-120 ms; see Figure 4, left panels) and visual N1 (150-190 ms; see Figure 4, right panels) components. Given the relative insensitivity of current source density analyses to distant and to tangential sources, the sharply focused peaks in the present current source density maps suggest a proximal radial current source beneath each current peak (Pernier et al., 1988). The peaks in the current source density analyses of the difference in P1 and N1 amplitude across the easy- and hard-Task$_1$ conditions suggested that the cross-modal dual-task interference caused by the greater processing overlap affected the amplitude of the response of extra-striate visual cortex in the P1 and N1 time windows.

Task_1 difficulty might lead to a variety of changes in neural activity, which could possibly influence Task_2 ERPs, as soon as there is any perceptual evidence that T_1 is a difficult tone (which might happen quite early, within 200 ms of the onset of T_1). This type of effect would be quite different from an effect reflecting interference associated with a central bottleneck in information processing. Although we cannot rule out this possibility definitively based on present results, we argue based on previous PRP research that the most likely locus of the Task_1 difficulty manipulation was at the central PRP bottleneck. First, an important previous result is he task difficulty manipulation we used here was shown to produce additive effects with SOA when manipulated in Task_2 of a typical PRP design (see Jolicœur et al., 2000), suggesting that the manipulation influences a stage of processing that occurs at or after the central bottleneck responsible for the PRP effect. Second, as can be seen in the present experiments, when manipulated in Task_1, we observe a carry-forward of Task_1 difficulty on Task_2, indicating that the manipulation occurs at or before the central bottleneck responsible for the PRP effect. Logically, this combined pattern of results implies that the Task_1 difficulty manipulation and SOA interfere with the same Task_2 bottleneck mechanisms[1]. This suggests that the observed P1 and N1 attenuation in the present experiment was caused by central processing overlap.

Nonetheless, we remain cautious and accept the possibility that the Task$_1$ difficulty manipulation could have influenced ERPs to T_2 via another mechanism than a direct effect of overlap with the PRP bottleneck. In any given PRP experiment, other limits that can lead to dual-task interference are present concurrently with the response selection and/or decision making bottleneck postulated to be the main source of interference responsible for the PRP effect (McCann & Johnston, 1992; Pashler & Johnston, 1989; Pashler, 1994), such as the limits in preparing for two concurrent tasks (i.e., maintaining two task sets concurrently). Pre-trial task preparation could not differ across the easy- and hard-Task$_1$ conditions because easy and hard trials were intermixed at random, making it impossible to anticipate one particular type of trial. However, given that the average T_1-T_2 SOA resulted in the presentation of T_2 about 90-100 ms before mean RT$_1$ in the hard-Task$_1$ condition and about 120-130 ms after mean RT$_1$ in the easy-Task$_1$ condition, differential post-trial task preparation could possibly have caused the P1 and N1 modulations by Task$_1$ difficulty, if central processing interfered with rapid dynamic shifts in task preparation that could take place in a time window of about 200 ms after central processes were freed from Task$_1$ (or 100 ms after response execution in Task$_1$). Alternatively, central interference could extend beyond the time during which the central mechanisms purportedly responsible for the PRP effect are busy processing T_1. Such post-bottleneck interference would presumably be a standard feature of PRP experiments, however, and would affect sensory responses associated with the T_2 as long as T_2 was presented within a certain time following T_1.

Even if we suppose that the attenuation of the P1 and N1 amplitude was not directly caused by the central bottleneck, but rather indirectly, via interference on rapid dynamic shifts in task preparation or via another form of post-bottleneck dual-task interference, these observations are important because they suggest a heretofore unsuspected locus of dual-task interference in the context of a cross-modal auditory-visual PRP paradigms. Extant models designed to explain results of PRP experiments postulate loci of interference that are much later than those that have been associated with the visual P1 and N1 components (see Pashler, 1994, for a review).

An important methodological issue in our study concerns the subtraction method we used to isolate ERPs to T_2 from overlapping ERPs generated by sensory, cognitive, and motor processes associated with the processing of T_1. Given that the SOA between T_1 and T_2 was the same for the easy- and hard-Task_1 conditions, sensory overlap was identical and could not have caused differences in ERPs to T_2 across the easy- and hard-Task_1 conditions. However, the central decision processes associated with the hard T_1 trials (middle two T_1 tone frequencies) were expected to require more time than those associated with the easy T_1 trials (lowest and highest T_1 tone frequencies). Furthermore, given the significant difference in mean RT_1 across the easy- and hard-Task_1 conditions, and the fixed T_1-T_2 SOA, which placed T_2 generally prior to the response on hard-

Task_1 trials and after the response in easy-Task_1 trials, it was necessary to anticipate that ERPs related to cognitive and motor activity in Task_1 would overlap differently with ERPs to T_2 across the easy- and hard-Task_1 conditions. For these reasons, we measured ERPs in trials in which only T_1 was presented (single-Task_1 trials) as well as ERPs in with T_1 and T_2 were presented (dual-task trials).

It is important to determine whether the attenuation of the extra-striate N1 component that we observed in the hard-Task_1 condition relative to the easy-Task_1 condition was truly produced by dual-task interference, as opposed to an artefact of the subtraction method used to isolate ERPs to T_2. Several considerations allow us to conclude that the results were not an artefact of the subtraction procedure. Task_1 performance was very similar across trial types. Indeed, accuracy to T_1 was identical in single-Task_1 and dual-task trials, and mean RT_1 was only slightly accelerated in dual-task trials in the hard-Task_1 condition. Furthermore, in the present design there were an equal number of single-Task_1 and dual-task trials, making it unlikely that single-Task_1 trials would be treated differently from dual-task trials (other than by the absence of Task_2-related processing). Therefore, the time course of underlying Task_1 processing (and as a consequence, the brain activity mediating Task_1 performance, including motor activity) was essentially the same across trial types, suggesting that the single-Task_1 condition provided a good model for Task_1 activity in dual-task trials. Given that voltage fields summate linearly (Luck, 2005), the raw ERPs in dual-task trials, which are the sum of $Task_1$ and $Task_2$ ERPs, can be corrected by subtracting the $Task_1$ ERPs estimated in single-$Task_1$ trials, allowing us to reveal the portion of the ERPs that were uniquely related to T_2 and processing in $Task_2$ (see Luck, 1998; Luck et al., 1993; Vogel et al., 1998, as examples of studies using similar subtraction methods).

Note that although mean RT_1 was very similar between trial types, the somewhat greater acceleration in mean RT_1 in dual-task trial compared to single-$Task_1$ trials in the hard-$Task_1$ condition (23.5 ms) than in the easy-$Task_1$ condition (0.3 ms) could potentially have resulted in an overestimation of the $Task_1$ difficulty effect on the P1 amplitude. We therefore shifted the single-$Task_1$ ERPs by the difference in mean RT_1 in both $Task_1$ conditions before performing the subtraction. After correction, there was still a marginally significant $Task_1$ difficulty effect on the P1 amplitude, suggesting that the P1 effect was not an artefact of our subtraction method. This correction would only have increased the $Task_1$ difficulty effect on the occipital N1, and therefore was not necessary.

The logic outlined in the previous paragraph requires that ERPs measured in single-$Task_1$ trials provide a faithful representation of $Task_1$ ERPs in dual-task trials. One issue that could be raised is whether the absence of T_2 in single-$Task_1$ trials either caused processing of T_1 to differ, or somehow gave rise to additional ERPs related to a violation of the expected presentation of T_2. We believe that neither of these issues compromised the present results. Consider first the issue of whether the absence of T_2 would somehow surprise or startle the subjects. It is very unlikely that the absence of T_2 caused special ERPs because there were an equal number of trials without T_2 as there were with T_2. Thus, the absence of T_2 was not a rare or special event. Rather, on average, every other trial contained only T_1. Furthermore, because both easy- and hard-$Task_1$ conditions were randomly presented in each block, and that SOA was identical for both $Task_1$ conditions, there could not be any differential T_2 expectancy between $Task_1$ conditions, and therefore this potential difference between trial types cannot explain the observed N1 modulation between $Task_1$ conditions. It is also worth mentioning that the time period of the N1 (and P1) would likely have already passed before the brain realized that T_2 did not appear in single-$Task_1$ trials. Moreover, the occipital N1 difference before the subtraction was greater than after the subtraction, and therefore the subtraction could not have artificially created the observed difference, especially that the decrease in negativity in the hard-$Task_1$ condition seen in the occipital N1 time range was preceded in a decrease in positivity in the P1 time range. Also, as previously noted, the subtraction flattened the baseline of the T_2-locked waveforms, which provides additional evidence that our subtraction method effectively removed overlapping $Task_1$ activity. Finally, as noted previously, response times and accuracy in $Task_1$ were very similar across single-$Task_1$ and dual-task conditions, suggesting strongly that processing in $Task_1$ unfolded essentially in the same way whether or not T_2 had been presented (as assumed in standard bottleneck models of the PRP paradigm; Pashler, 1994).

Some researchers have suggested that the CNV represents a state of cortical excitability that determines the amplitude of an ERP response to a stimulus. For example, by probing different phases of the CNV component, Rockstroh, Muller, Wagner, Cohen, and Elbert (1993) suggested that with an increasing level of surface negativity, the N1/P3 peaks of the probe were larger. As can be seen in Figure 2, the single-Task_1 negative shift is greater in the easy-Task_1 condition than in the hard-Task_1 condition. Therefore, if the sustained negativity seen in the single-Task_1 ERPs represents CNV-like activity, T_2 would have appeared into a more excitable state in the easy-Task_1 condition than in the than in the hard-Task_1 condition, leading to the observed P1 and N1 modulations. However, the mapping of the activity is lateralized as a function of the response hand used to execute the first response (i.e., activity in the left hemisphere with right hand response), which suggests that the single-Task_1 ERP waveforms more likely reflects response-related activity. Moreover, not only is the amplitude of the negative shift reduced in the hard-Task_1 condition, but its onset latency is increased by about 200 ms, as is the mean RT_1. As discussed above, it remains possible that central processing interfered with dynamic shifts in task preparation. If this is the case, it is possible that a CNV-like preparation related activity could be delayed in the same manner as RT_2s. However, in this case, the difference in onset latency of the negative shift should have been in the order of 70 ms, as the mean RT_2 difference, and not in the order of 200 ms, as the RT_1 difference. Thus, we believe that the evidence favours the hypothesis that the negative shift in the single-$Task_1$ ERP waveforms reflected response-related activity of the first task, and not CNV-like anticipation/preparation activity of T_2.

It is important to note, however, that even if the single-$Task_1$ negative shift was a CNV-like anticipation/preparation wave, the difference in amplitude (and onset latency) observed between $Task_1$ conditions could only have been caused by our manipulation. Indeed, as discussed above, the experiments in the present study were carefully designed so that no differential task preparation, nor differential anticipation to T_2 could be caused by anything other than our $Task_1$ manipulation. Therefore, even if it were true that the single-$Task_1$ negativity shift was a CNV-like anticipation/preparation wave, and even if the CNV-like enhanced surface negativity represents a state of enhanced neural excitability that causes enhanced ERP-deflections, the difference in surface negativity observed in the present study could only be caused by our $Task_1$ difficulty manipulation, and therefore would only be a consequence of dual-task interference, and not an alternative interpretation of our results. In this view, a CNV-like wave occurred earlier in the easy $Task_1$ condition than in the difficult $Task_1$ condition presumably because central mechanisms are required to trigger the CNV, which, in turn, would have modulated the excitability of cortical responses to the T_2 stimulus. Further research would be required to confirm this interpretation of the results.

The modulation of the visual occipital, likely extra-striate visual cortex, P1 and N1 in this experiment is therefore the first direct demonstration of dual-task interference on early sensory-perceptual processing in a cross-modal PRP paradigm.

Another important result is that the occipital N1 was greater contralateral than ipsilateral to the target, and that this laterality effect was not affected by Task_1 difficulty. The laterality effect could theoretically have been due to the contamination of the N2pc (which starts around 180 ms post-visual display) in the second half (170-190 ms) of the occipital N1 time-window. However, the laterality effect was also present in the first half (150-170 ms) of the occipital N1, which is inconsistent the N2pc overlap hypothesis. Rather, the laterality effect observed here more likely reflects a pre-attentive relevant-feature detection process that precedes the spatial allocation of attention on the target, and can be observed as a greater negativity in the N1 time range (i.e., about 140-190 ms post-visual display: Hopf et al., 2004). The absence of an interaction of laterality and Task_1 difficulty suggest that concurrent Task_1 processing does not interfere with pre-attentive relevant-feature detection processes, as suggested by the lack of Task_1 interference on Task_2 accuracy when a masked T_2 required a response as to the location of the uniquely colored item in a multi-item bilateral display (see Brisson & Jolicœur, 2007a; control experiment).

Experiment 1 also enabled us to replicate two important findings recently reported by Brisson and Jolicœur (2007a, 2007b), that is the attenuation of the N2pc and the delay in the SPCN onset latency as concurrent central attentional load increased in the PRP paradigm. Therefore, although concurrent Task_1 processing does not interfere with the detection of relevant features, it interferes with the deployment of attention to the location of the item containing the relevant feature, and delays the consolidation of the item in visual-short term memory.

The P3 component was also attenuated as concurrent central load increased, a result that replicates previous studies (e.g., Dell'Acqua, Jolicœur, Vespignani, & Toffanin, 2005; Luck, 1998). No significant P3 latency effect was observed, however, although latency differences tended to go in the same direction as in these previous studies.

Experiment 2

In Experiment 1, T_2 required a speeded 4-alternative discrimination response. Experiment 2 investigated whether the occipital N1 effect observed in Experiment 1 would also be present if Task_2 was a speeded detection task rather than a discrimination task. The main reason to investigate this question is that the presence or absence of a Task_1 difficulty effect on the occipital N1 when T_2 is associated to a detection task as opposed to a discrimination task can help us determine the nature of the interference observed in Experiment 1. Vogel and Luck (2000) demonstrated that the occipital N1 elicited by identical stimuli was larger for discrimination tasks than for detection tasks, and that this difference was present both for color- and form-based discriminations. Because this N1 discrimination effect was equivalent for easy and hard discriminations, Vogel and Luck (2000) argued that the occipital N1 effect observed in their study reflected perceptual discrimination processes, and not a broader resource-based effect. Therefore, if concurrent processing of the tone interfered solely with the perceptual processes reflected by the discrimination processes inferred by Vogel and Luck (2000), $Task_1$ difficulty should no longer modulate the occipital N1 when T_2 is associated with a detection task, or at least do so to a lesser extent. One might hypothesize, for example, that some dual-task interference in Experiment 1 took place at the level of mechanisms required for discriminating or classifying T_2. Vogel and Luck's (2000) arguments, and evidence, that the N1 is sensitive to discriminative processes could provide a basis for the link between dual-task interference in the PRP paradigm and modulations of the visual N1.

Experiment 2 was very similar to Experiment 1. We used the same stimuli and the same task for $Task_1$ as in Experiment 1. $Task_2$ was changed, however, to a simple detection task by asking subjects to press a button as quickly as possible as soon as T_2 (a visual stimulus identical to that used in Experiment 1) was presented, regardless of the details of T_2. The main question was whether we would observe dual-task interference on the amplitude of the visual N1 response elicited by T_2 now that $Task_2$ no longer required discrimination.

Methods

Participants

Thirty undergraduate students from the Université de Montréal participated in this experiment for financial compensation. Six participants were excluded for reasons that are outlined below. Thus 24 participants (18 women), aged 19-30 (mean age: 23 years) remained in the sample. All participants were neurologically intact and reported having normal hearing and normal or corrected-to-normal visual acuity and color vision. Written consent was obtained from each participant at the beginning of the experiment. The procedure was vetted by the appropriate ethics committee at the Université de Montréal. One participant also participated in Experiment 1.

Stimuli and procedure

The stimuli and procedure were identical to those used in Experiment 1with one exception. Whereas $Task_2$ required a speeded 4-alternative discrimination response to the location of the gap in T_2 in Experiment 1, $Task_2$ required a speeded detection response to the visual display in Experiment 2. As in Experiment 1, responses to the visual display were made with the fingers of the left hand. All four response keys used to respond to T_2 in Experiment 1 were also used in Experiment 2 (5 participants responded to the visual display by pressing the “Z” key on the keyboard, 7 responded by pressing “X”, 7 responded by pressing “C”, and

5 responded by pressing the “V” key). Because trials were initiated by pressing the “N” and “V” keys simultaneously with the right and left index fingers respectively, the “Z,” “X,” “C,” and “V” keys had to be pressed with the little, ring, middle, and index fingers respectively, as was the case in Experiment 1.

EEG Recording and Analysis

The same EEG and EOG procedures were used as in Experiment 1. Six participants were excluded because less then 144 trials (i.e., 60% of trials) remained after trial rejection in at least one of the four condition (easy- and hard-Task$_1$ condition) × trial type (single-Task$_1$ and dual-task) cells. Of the remaining 24 participants, an average of 86% of easy-Task$_1$ trials (85% of single-Task$_1$ trials and 87% of dual-task trials), and 88% of hard-Task$_1$ trials (87% of single-Task$_1$ trials and 88% of dual-task trials) remained after trial rejection. None of these participants had residual eye movements that deviated more then 0.2° (i.e., HEOG > 3.2 μV) towards T_2 (dummy-coded as in Experiment 1) after rejection criteria was applied (this was not surprising given that no specific instructions differentiated the red vs. green squares in T_2 in Experiment 2, and so there was no reason to expect any desire to move the eyes toward one or the other square in the T_2 display).

Behavioral and electrophysiological analyses were identical to those performed in Experiment 1 with the following exceptions. In Experiment 2, the entire visual display played the role of T_2. Therefore, contrary to

Experiment 1, laterality of T_2 had no meaning, and so laterality (ipsilateral vs. contralateral) was not included as a factor in the occipital P1 and N1 analyses. Moreover, since the N2pc and SPCN are defined as greater negativities contralateral to a target, these components can not be elicited in this experiment, and therefore were not analysed. Trial type was also included as an additional within subject factor in the T_2 accuracy analysis to evaluate the propensity to produce anticipatory responses.

Results

Behavioral results

Single-Task_1 and dual-task trial accuracy and mean RTs for T_1, and dual-task trial accuracy, mean RTs for T_2 in each Task_1 condition, and mean SOA, are shown in Table 2. As in Experiment 1, mean RT_1 was significantly longer, $F(1, 23) = 35.8$, $p < .0001$, and T_1 accuracy was significantly lower, $F(1, 23) = 73.3$, $p < .0001$, in the hard-Task_1 condition than in the easy-Task_1 condition. Accuracy for T_1 was identical for single-Task_1 trials and dual-task trials, $F(1, 23) = 1.75$, $p > .19$, and there was no Task_1 condition × trial type interaction, $F(1, 23) = 1.28$, $p > .27$. As in Experiment 1, mean RT_1 differences in single-Task_1 trials and dual-task trials in the hard-Task_1 condition (23.2 ms) and in the easy-Task_1 condition (6.8 ms) were small, but significantly longer in single-Task_1 trials, $F(1, 23) = 7.5$, $p < .015$. The Task_1 condition × trial type interaction was also significant, $F(1, 23) = 6.5$, $p < .02$.

RT_2 was 115 ms longer in the hard-$Task_1$ condition than in the easy-$Task_1$ condition, $F(1, 23) = 47.0$, $p < .0001$, indicating that the desired carry-forward effect of $Task_1$ difficulty on $Task_2$ was obtained. There was no effect of $Task_1$ condition ($F < 1$) nor trial type (both $Fs < 1$) for T_2 accuracy, although there was a significant interaction between these two factors, $F(1, 23) = 7.3$, $p < .015$. Importantly, T_2 accuracy was 98% or better in all $Task_1$ condition by trial type cells, indicating that there were very few anticipatory responses to T_2.

========== Please insert Table 2 about here ==========

Electrophysiological results

Occipital P1 and N1

Grand-average waveforms locked to T_2 onset (i.e., T_1 + SOA) are shown in Figure 7 as a function of $Task_1$ condition and trial type at PO7/PO8 electrode sites. The dual-task minus single-$Task_1$ difference waves for both $Task_1$ conditions are shown in Figure 8. As in Experiment 1 the subtraction procedure flattened the pre-T_2 baseline, indicating that it was effective in removing systematic $Task_1$ overlap from the T_2-locked visual ERPs. Contrary to Experiment 1, no $Task_1$ difficulty effect was observed on the P1 amplitude ($F < 1$). The amplitude of the occipital N1, however, was significantly smaller in the hard-$Task_1$ condition (mean amplitude = -2.76 μV) than in the easy-$Task_1$ condition (mean amplitude of -3.37 μV; $F(1, 23) = 4.36$, $p < .05$, and as in Experiment 1, current source density maps (see

Figure 9) suggest that the occipital N1 effect reflects the activity of a neural generator in extra-striate visual cortex (Pernier et al., 1988). Subsequent analyses revealed, however, that the $Task_1$ difficulty effect was only present in the second half (170-190 ms) of the occipital N1 time window, $F(1, 23) = 10.80$, $p < .003$. There was no significant effect in the earlier 150-170 ms post-T_2 time window ($F < 1$).

======= Please insert Figure 7, Figure 8 and Figure 9 about here =======

P3 component

The P3 results replicate the results found in Experiment 1. As can be seen in Figure 10, the amplitude of the P3 component, which was maximal at POz and corresponded with the usual bilateral centro-parietal distribution, was smaller in the hard-$Task_1$ condition (mean amplitude of 7.10 µV) than in the easy-$Task_1$ condition (mean amplitude of 9.56 µV, $F(1, 23) = 25.17$, $p < .001$). However, the jackknife analysis based on the time at which the waveform reached 6 µV, starting at 250 ms post-visual display revealed that the 19 ms delay was not significant ($F(1, 23) = 1.04$; $p > .32$).

========== Please insert Figure 10 about here ==========

Discussion

Although no modulation of the occipital P1 was observed, the occipital N1 modulation by $Task_1$ difficulty observed in Experiment 1 was replicated in the present experiment. As in Experiment 1, the occipital N1 elicited by identical visual displays associated to identical tasks was smaller when task overlap was maximized (hard-Task$_1$ condition) than when task overlap was minimized (easy-Task$_1$ condition) and the current source density maps are consistent with a neural generator in extra-striate visual cortex (see Figure 8). However, contrary to Experiment 1, in which the occipital N1 modulation was observed in both the first half (150-170 ms) and second half (170-190 ms) of the N1 time window, the N1 modulation in Experiment 2 was observed only in the 170-190 ms time window.

The fact that the occipital N1 modulation was smaller in Experiment 2 than in Experiment 1, and only present in the later half (170-190 ms) of the N1 time window, suggests that at least part of the occipital N1 modulation observed in Experiment 1 may have been caused by interference on sensory-perceptual discriminative processes (Vogel & Luck, 2000). It can be argued that a minimal degree of discrimination was also required in Experiment 2, despite the fact that T_2 required a detection response, because T_2 had to be discriminated from T_1, and the presence of T_2 had to be discriminated from the absence of T_2. Thus, it is theoretically possible that the effect of dual-task interference on the occipital N1 entirely reflects a modulation of discriminative processing. However, it is also possible that part of the dual-task interference we observed on the amplitude of the N1 in both experiments reflects a more general aspect of the visual occipital N1 response. The present N1 results are important, because they reveal that dual-task interference on perceptual processing also occurs when easy, simple T_2 detection is required.

The P3 component results also replicated those from Experiment 1 and demonstrated that P3 amplitude can also be modulated by $Task_1$ processing when $Task_2$ is a detection task.

General Discussion

The occipital N1 was attenuated when a visual target (T_2) was presented while participants were performing a capacity demanding speeded auditory choice task, both when T_2 was associated to a discrimination task (Experiment 1) and when it was associated to a detection task (Experiment 2). These occipital N1 effects of $Task_1$ difficulty are the earliest dual-task interference effects ever reported in the context of the PRP paradigm. The time range of the interference (N1: 150-190 ms post-T_2) and the posterior scalp distribution of the current source density maps of the effects (over the occipital cortex) strongly suggest that concurrent processing underlying dual-task interference in the context of a PRP paradigm can interfere with some aspect of sensory-perceptual processes that take place well before response selection, despite the fact that the two stimuli stimulated distinct sensory systems.

The visual P1 (100-120 ms post-T_2) was also attenuated in Experiment 1, when T2 was associated to a discrimination task. These results suggest impressively early attenuation of visual sensitivity can be caused by dual-task interference. Although the Grand Average waveforms in Experiment 2 also suggested an attenuated P1 response under conditions of greater dual-task interference, this effect was not statistically significant. However, it is also clear that the interference effects for the N1 response observed in Experiment 2 were smaller than those observed in Experiment 1. Consequently, it is possible that there was interference with the P1 wave in Experiment 2, but simply too small to be statistically reliable. To be sure, our *a priori* expectations concerning differences across Experiments 1 and 2 were primarily for the N1 wave. Consequently, our interpretation of the P1 effects as resulting from dual-task interference must remain tentative and would benefit from replication.

The strong overlap observed between brain regions engaged in response selection and those engaged in perceptual discrimination (Jiang & Kanwisher, 2003) suggested that dual-task interference on perceptual processes may occur in the PRP paradigm when a difficult Task_2 discrimination was required. The present occipital N1 results not only provide the first direct electrophysiological evidence that dual-task interference on perceptual processing effectively occurs when difficult T_2 discrimination is involved (Experiment 1), but also when simple T_2 detection is required (Experiment 2). Moreover, the occipital N1 modulation observed in Experiment 2 suggests that Task_1 processing interfered with the occipital N1 discriminative effect (see Vogel & Luck, 2000), but perhaps also with a more general aspect of the visual occipital N1. However, it can be argued that a minimal degree of discrimination was required in Experiment 2, because T_2 had to be discriminated from T_1 and the presence of T_2 had to be discriminated from the absence of T_2. Thus, the hypothesis that the effect of dual-task interference on the occipital N1 entirely reflects a modulation of discriminative processing cannot be entirely excluded.

Note that the occipital N1 was attenuated, not delayed. This suggests that the nature of the interference was to reduce processing efficiency during concurrent central processing in $Task_1$ relative to the processing of T_2 alone, rather than to prevent concurrent processing altogether. This could explain why studies using the locus-of-slack method did not detect this form of perceptual interference in the PRP paradigm. Indeed, an underadditive effect of perceptual degradation and decreasing SOA would be predicted, even though parallel processing was less efficient, as long as the period of cognitive slack (postponement of central processing in $Task_2$) was sufficiently long to absorb both the effect of a degradation manipulation and the lowered efficiency of processing due to the sensory-perceptual dual-task interference reflected by the attenuation of the visual N1 revealed by Experiments 1 and 2.

In Experiment 1, the occipital N1 was larger contralateral than ipsilateral to T_2. This effect was not modulated by the $Task_1$ difficulty manipulation, suggesting that concurrent $Task_1$ processing did not interfere with pre-attentive feature detection processes (see Hopf et al., 2004). However, the N2pc was attenuated and the SPCN was delayed. These results replicate those observed in Brisson and Jolicœur (2007a, 2007b), and demonstrate once again that central processing required to perform a speeded auditory choice task interferes with the deployment of visual-spatial attention to the location of the target (i.e., N2pc), and delays encoding in visual short-term memory (SPCN). We note, however, that the magnitude of the SPCN latency effect does not account for the entirety of the usual delay in RT_2 in the PRP paradigm. Nonetheless, these interference effects are important for theory and a complete understanding of dual-task interference because they suggest that dual-task interference occurs at a number of levels, including relatively early processes involved in the deployment of visual-spatial attention and encoding into visual short-term memory (see also Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006a, 2006b).

Although this study does not contradict the claim that response selection is an important locus of interference in the cross-modal PRP paradigm, it provides strong electrophysiological evidence that, contrary to what is assumed by virtually all models of PRP interference, concurrent processing of a first auditory target also interferes with sensory-specific processing of a second visual target, as early as 150-170 ms (and perhaps even as early as 100-120 ms) post-T_2 when T_2 is associated to a discrimination task, and as early as 170-190 ms post-T_2 when T_2 is associated to a detection task.

References

Brisson, B., & Jolicœur, P. (2007a). Electrophysiological evidence of central interference in the control of visuospatial attention. *Psychonomic Bulletin & Review*, 14, 126-132.

Brisson, B., & Jolicœur, P. (2007b). A psychological refractory period in access to visual short-term memory and the deployment of visual-spatial attention: Multitasking processing deficits revealed by event-related potentials. *Psychophysiology*, 44, 323-333.

Dell'Acqua, R., Jolicœur, P., Vespignani, F., & Toffanin, P. (2005). Central processing overlap modulates P3 latency. *Experimental Brain Research*, 165, 54-68.

Dell'Acqua, R., Sessa, P., Jolicœur, P., & Robitaille, N. (2006), Spatial attention freezes during the attentional blink. *Psychophysiology*, 43, 394-400.

Donchin, E. (1981). Surprise!... Surprise? *Psychophysiology*, 18, 493-513.

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

Hopf, J.M., Boelmans, K., Schoenfeld, M.A., Luck, S.J., & Heinze, H.J. (2004). Attention to features precedes attention to locations in visual search: evidence from electromagnetic brain responses in humains. *The Journal of Neuroscience*, 24, 1822-1832.

Jiang Y., & Kanwisher, N. (2003). Common neural mechanisms for response selection and perceptual processing. *Journal of Cognitive Neuroscience*, 15, 1095-1110.

Johnston, J.C., McCann, R.S., & Remington, R.W. (1995). Chronometric evidence for two types of attention. *Psychological Science*, 6, 365-369.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded Task1 decisions. *Memory & Cognition*, 26, 1014-1032.

Jolicœur, P. (1999a). Dual-task interference and visual incoding. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 596-616.

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

Jolicœur, P., Brisson, B., & Robitaille, N. (2007) *Dissociation of the N2pc and Sustained Posterior Contralateral Negativity in a speeded choice response task*. Manuscript submitted for publication. Département de psychologie, Université de Montréal, Montréal, Québec, Canada.

Jolicœur, P., Dell'Acqua, R., & Crebolder, J. (2000). Multitasking performance deficits: Forging some links between the attentional blink and the psychological refractory period. In S.~Monsell and J. Driver (Eds.), *Control of cognitive processes: Attention and Performance, XVIII* (pp. 309-330). Cambridge, MA: MIT Press.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006a). On the control of visual spatial attention: Evidence from human electrophysiology. ***Psychological Research***, 70, 414-424.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006b). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. ***European Journal of Cognitive Psychology***, 18, 560-578.

Kiesel, A., Miller, J., Jolicœur, P., & Brisson, B. (2007). Measurement of ERP latency differences: A comparison of single-participant and jackknife-based scoring methods. Manuscript submitted for publication, Julius-Maximilians University of Würzburg.

Klaver, P., Talsa, 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. (1998). Sources of dual-task interference: evidence from human electrophysiology. ***Psychological Science***, 9, 223-227.

Luck, S.J. (2005). ***An introduction to the event-related potential technique***. Cambridge MA: The MIT press.

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., McDermott, M.T., & 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.

Mangun, G.R. (1995). Neural mechanisms of visual selective attention. *Psychophysiology*, 32, 4-18.

McCann, R.S., & Johnston, J.C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 471-484.

McCollough, A.W., Machizawa, M.G., & Vogel, E.K. (2007) Electrophysiological measures of maintaining representations in visual working memory. *Cortex*, 43, 77-94.

Meyer, D.E., & Kieras, D.E. (1997). A computational theory of executive cognitive processes and human multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. *Psychological Review*, 104, 749-791.

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

Navon, D., & Miller, J. (2002). Queuing of sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology*, 44, 193-251.

Oriet, C., & Jolicœur, P. (2003). Absence of perceptual processing during reconfiguration of task-set. *Journal of Experimental Psychology: Human Perception and Performance*, 29, 1036-1049.

Osman, A., & Moore, C.M. (1993). The locus of dual-task-interference: Psychological refractory effects on movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 1292-1312.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. *Psychological Bulletin*, 116, 220-244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapoping tasks. *Quarterly Journal of Experimental Psychology*, 41A, 19-45.

Pernier, J., Perrin, F., & Bertrand, O. (1988). Scalp current density fields: Concept and properties. *Electroencephalography and Clinical Neurophysiology*, 69, 385-389.

Prime, D., Chénier, H., & Jolicœur, P. (2006, April). Object representations are held in visual short-term memory during mental rotation. Poster at the Annual Meeting of the Cognitive Neuroscience Society, San Francisco, CA, USA, April 8-11.

Robitaille, N., & Jolicœur, P. (2006). Fundamental properties of the N2pc as an index of spatial attention: effect of masking. *Canadian Journal of Experimental Psychology*, 60, 101-111.

Rockstroh, B., Muller, M., Wagner, M., Cohen, R., & Elbert, T. (1993). "Probing" the nature of the CNV. ***Electroencephalography and Clinical Neurophysiology***, 87, 235-241.

Schweickert, R. (1980). Critical-path scheduling of mental processes in a dual-task. ***Science***, 209, 704-706.

Sommer, W., Leuthold, H,. & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. ***Psychonomic Bulletin & Review***, 8, 81-88.

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.

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

Van Selst, M., & Johnston, J.C. (1996, November). Dual-task interference that cannot be attributed to output interference. Paper presented at the 37th Annual Meeting of the Psychonomics Society, Chicago.

Van Selst, M., & Jolicœur, P. (1994). A solution to the effect of sample size on outlier elimination. ***Quaterly Journal of Experimental Psychology: Human Experimental Psychology***, 47A, 631-650.

Verlegger, R. (1988). Event related potentials and cognition: a critique of the context updating hypothesis and an alternative interpretation of the P3. ***Behavioral Brain Science***, 11, 343-427.

Vogel, E.K., & Luck, S.J. (2000) The visual N1 component as an index of a discrimination process. *Psychophysiology*, 37, 190-203.

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.

Welford, A.T. (1952). The "psychological refractory period" and the timing of high-speed performance — A review and a theory. *British Journal of Psychology*, 43, 2-19.

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.

Wyszecki, G., Stiles, W.S. (1982). *Color science: Concepts and methods, quantitative data and formulae* (2nd Ed.) New York: John Wiley & Sons.

Acknowledgments

This research was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Research Chairs Program, and the Université de Montréal awarded to PJ and by an NSERC postgraduate scholarship awarded to BB. We would also like to thank Manon Robert, Nathalie Bouloute, Alexandrine Deland-Bélanger, Hugo Chénier, and Kevin Murphy for helping us with data acquisition, Alexia Ptito, Nicolas Robitaille, and Émilie Leblanc for helpful discussion, and Steve Luck and an anonymous reviewer for constructive comments on a previous version of the manuscript.

Footnote

1. In a previous study (Brisson & Jolicœur, 2007b), where both SOA and Task_1 difficulty where manipulated, we observed, at the shortest SOA, equivalent effect sizes of Task_1 difficulty in RT_2 (220 ms) as in RT_1 (183 ms: easy-Task_1 = 589 ms, hard-Task_1 = 772 ms), demonstrating a full carry-forward of Task_1 difficulty on RT_2. With the additivity of the task difficulty effect when manipulated in Task_2, this result strengthens the claim that the task difficulty effect is entirely in the central bottleneck. Moreover, the carry-forward effect of Task_1 difficulty on RT_2 diminished with increasing SOA (220 ms Task_1 difficulty effects in the 300 ms SOA, 130 ms in the 650 ms SOA, and 9 ms in the 1000 ms SOA condition, leading to a robust SOA × Task_1 difficulty interaction [$F(2,30) = 34.53$, $p < .0001$]), providing evidence that the Task_1 difficulty effect is short-lasting, as is the PRP effect when SOA is manipulated. Results were presented independently for the SOA and Task_1 difficulty manipulations in the published article.

Table 1. Mean RT to T_1 in Single-Task$_1$ Trials and Mean Accuracy and RT to T_1 and T_2 in Dual-Task Trials for Each Task$_1$ Condition in Experiment 1.

Task$_1$ Condition	Single-Task$_1$		Dual-task			
	RT$_1$	Acc$_1$	RT$_1$	Acc$_1$	RT$_2$	Acc$_2$
Easy-Task$_1$	503.6	96.6	503.3	96.3	651.3	94.7
	(16.8)	(0.6)	(17.6)	(0.6)	(17.7)	(0.9)
Hard-Task$_1$	716.5	85.2	693.0	84.9	720.8	93.2
	(26.7)	(1.6)	(27.2)	(1.5)	(19.5)	(0.9)

Mean SOA = 629 (16) ms; RT$_1$ = reaction time to T_1; RT$_2$ = reaction time to T_2.

Acc$_1$: accuracy for T_1; Acc$_2$: accuracy for T_2; SEM in parentheses.

Table 2. Mean RT to T_1 in Single-Task$_1$ Trials and Mean Accuracy and RT to T_1 and T_2 in Dual-Task Trials for Each Task$_1$ Condition in Experiment 2.

Task$_1$ Condition	Single-Task$_1$		Dual-task			
	RT$_1$	Acc$_1$	RT$_1$	Acc$_1$	RT$_2$	Acc$_2$
Easy-Task$_1$	582.8	94.3	576.0	93.5	314.2	98.4
	(38.8)	(1.0)	(36.9)	(1.0)	(16.2)	(0.4)
Hard-Task$_1$	795.9	82.7	772.7	82.6	431.7	99.0
	(67.6)	(1.6)	(65.1)	(1.5)	(29.4)	(0.1)

Mean SOA = 694 (35) ms; RT$_1$ = reaction time to T_1; RT$_2$ = reaction time to T_2.

Acc$_1$: accuracy for T_1; Acc$_2$: accuracy for T_2; SEM in parentheses.

Figure Captions

Figure 1. Stimulus sequence in Experiment 1 and 2. Dual-task trials are illustrated in the top panel and single-Task_1 trials are illustrated in the bottom panel. The squares in the visual display were equiluminant red or green in the actual experiment.

Figure 2. Grand-average event-related potential (ERP) waveforms in Experiment 1 time-locked to T_1 onset + SOA (i.e., T_2 onset in dual-task trials) at ipsilateral and contralateral PO7/PO8 electrode sites relative to the location of T_2 (left vs. right visual field) for both Task_1 conditions.

Figure 3. The dual-task minus single-Task_1 difference waves at ipsilateral and contralateral PO7/PO8 electrode sites relative to the location of T_2 (left vs. right visual field) for both Task_1 conditions.

Figure 4. Current source density maps computed from the average voltage in the 100-120 ms (occipital P1; left panels) and in the 150-190 ms (occipital N1; right panels) post-T_2 onset time window for the easy- and hard-Task_1 conditions in Experiment 1, as well as the current source density map for the occipital P1 and occipital N1 effect, computed from the easy-Task_1 minus hard-Task_1 difference wave. The data were rearranged across trials such that the left electrodes in the figure represent the electrodes contralateral to T_2 and the right electrodes represent the electrodes ipsilateral to T_2.

Figure 5. Contralateral minus ipsilateral difference waves time-locked to T_2 onset at PO7/PO8 for the easy- and hard-Task_1 conditions.

Figure 6. The dual-task minus single-Task_1 difference waves at central POz, Pz, and Cz electrode sites for both Task_1 conditions.

Figure 7. Grand-average event-related potential (ERP) waveforms in Experiment 2 time-locked to T_1 onset + SOA (i.e., T_2 onset in dual-task trials) at PO7/PO8 electrode sites for both $Task_1$ conditions.

Figure 8. The dual-task minus single-$Task_1$ difference waves at PO7/PO8 electrode sites relative to the location of T_2 (left vs. right visual field) for both $Task_1$ conditions.

Figure 9. Current source density maps in the 150-190 ms (occipital N1) post-T_2 onset time windows for the easy- and hard-$Task_1$ conditions in Experiment 2, as well as current source density map for the occipital N1 effect computed from the easy-$Task_1$ minus hard-$Task_1$ difference wave. To compute the current source density maps, T_2 was arbitrarily defined as the red or green square and the data were rearranged across trials such that the left electrodes in the figure represent the electrodes contralateral to T_2 and the right electrodes represent the electrodes ipsilateral to T_2.

Figure 10. The dual-task minus single-$Task_1$ difference waves at central POz, Pz, and Cz electrode sites for both $Task_1$ conditions.

Figure 1

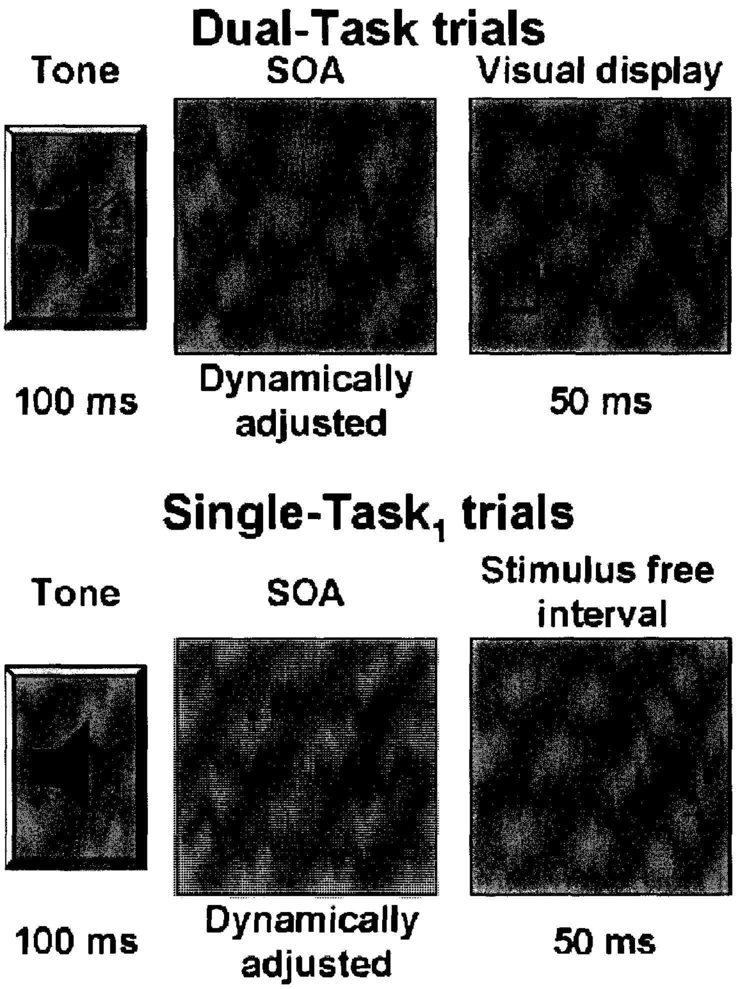

Dual-Task trials
Tone
SOA
Visual display
100 ms
Dynamically adjusted
50 ms
Single-Task$_1$ trials
Tone
SOA
Stimulus free interval
100 ms
Dynamically adjusted
50 ms

Figure 2

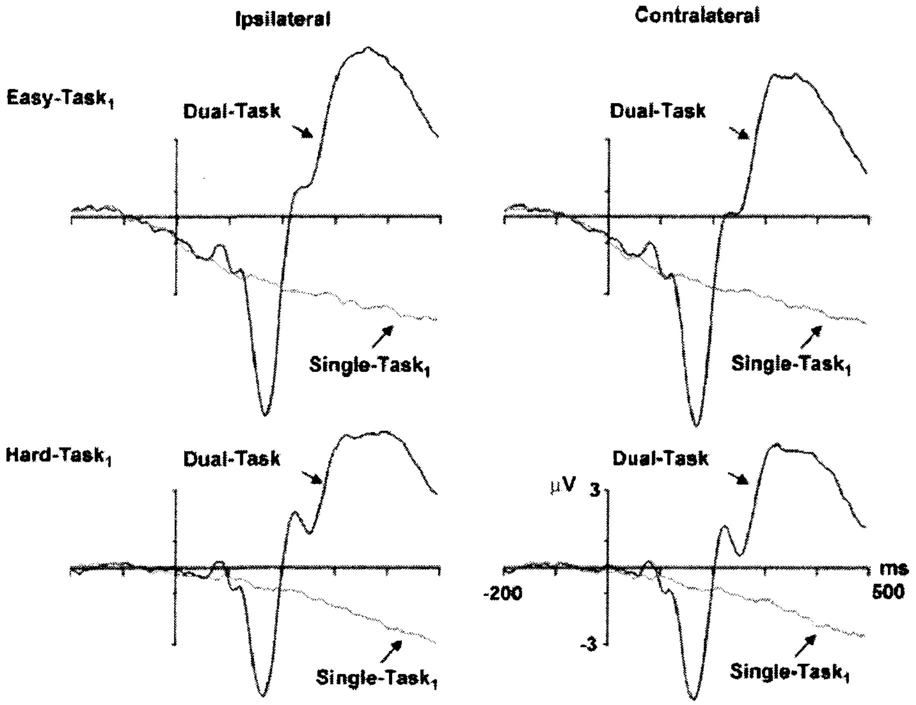

Ipsilateral
Contralateral
Easy-Task$_1$
Dual-Task
Single-Task$_1$
Dual-Task
Single-Task$_1$
Hard-Task$_1$
Dual-Task
Single-Task$_1$
Dual-Task
μV 3
-3
-200
500
ms
Single-Task$_1$

Figure 3

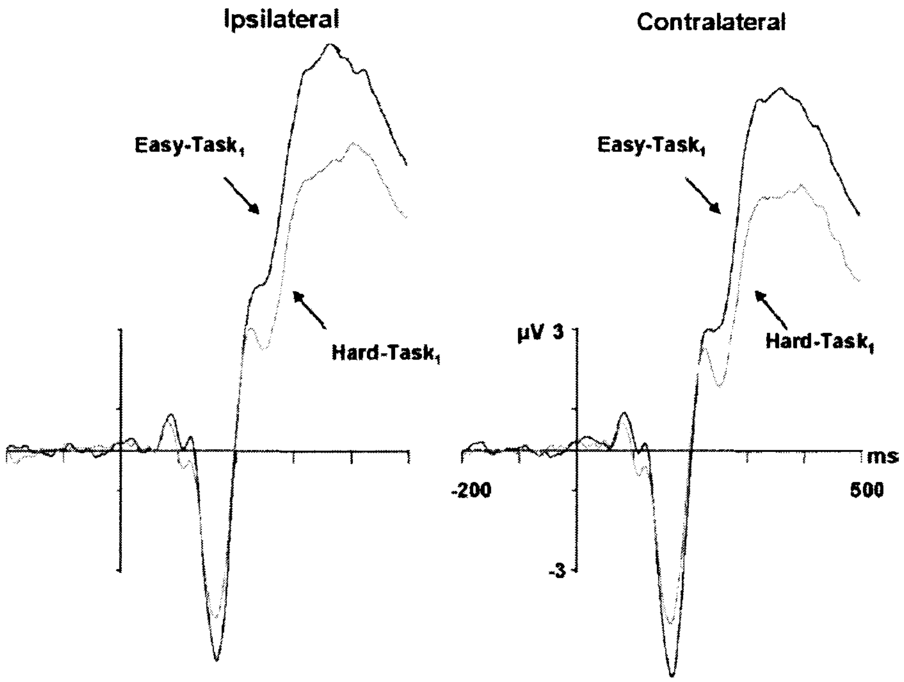

Ipsilateral
Contralateral
Easy-Task$_1$
Hard-Task$_1$
Easy-Task$_1$
Hard-Task$_1$
µV 3
-3
-200
500
ms

Figure 4

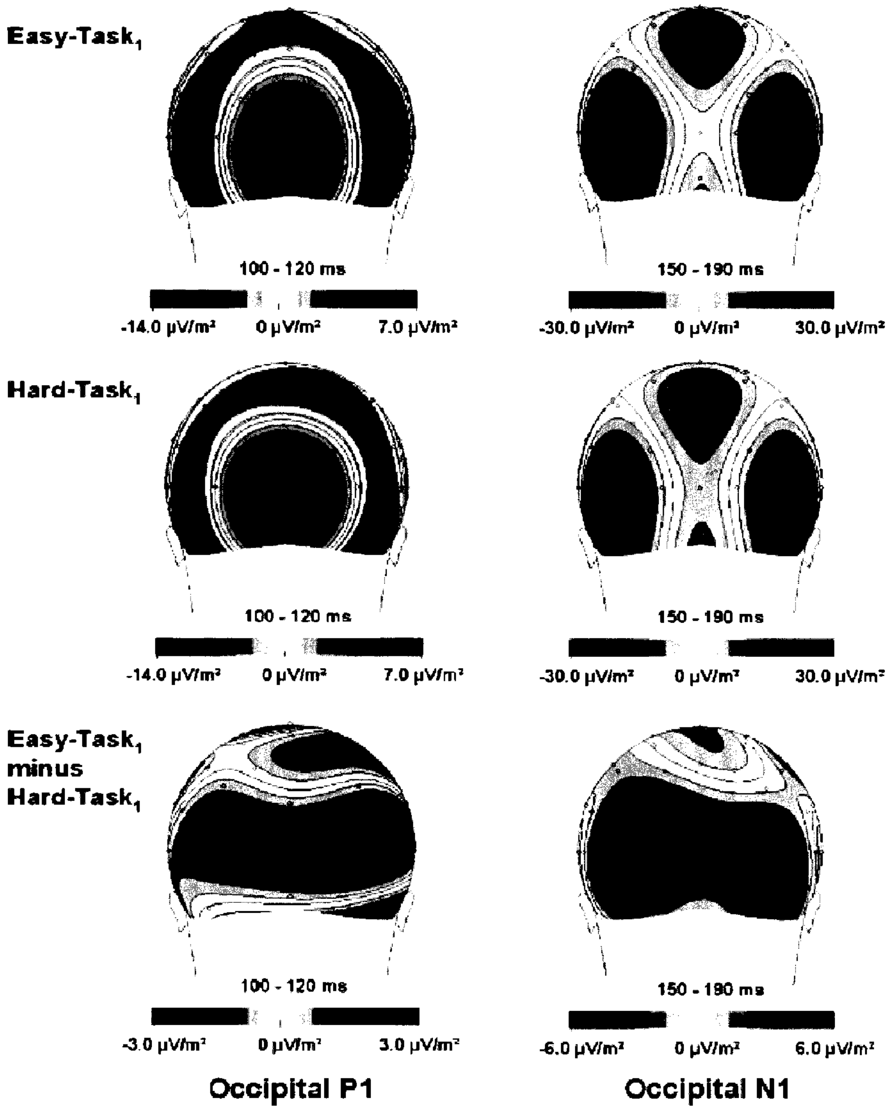

Easy-Task$_1$
100 - 120 ms
-14.0 µV/m²
0 µV/m²
7.0 µV/m²
150 - 190 ms
-30.0 µV/m²
0 µV/m²
30.0 µV/m²
Hard-Task$_1$
100 - 120 ms
-14.0 µV/m²
0 µV/m²
7.0 µV/m²
150 - 190 ms
-30.0 µV/m²
0 µV/m²
30.0 µV/m²
Easy-Task$_1$ minus Hard-Task$_1$
100 - 120 ms
-3.0 µV/m²
0 µV/m²
3.0 µV/m²
150 - 190 ms
-6.0 µV/m²
0 µV/m²
6.0 µV/m²
Occipital P1
Occipital N1

Figure 5

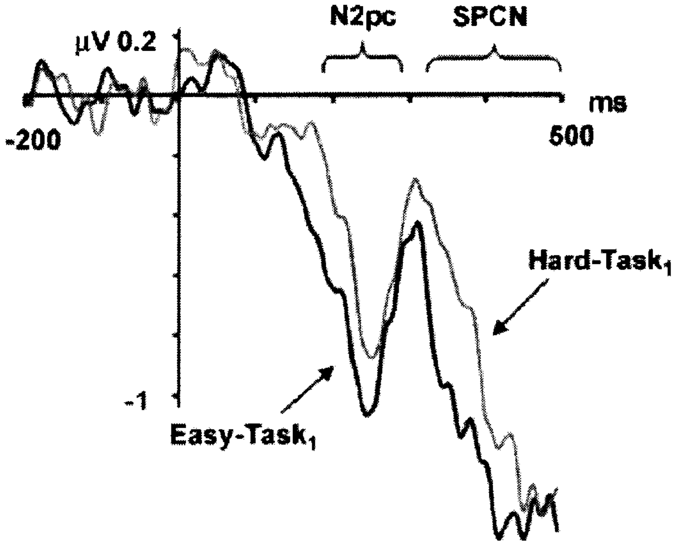


Figure 6

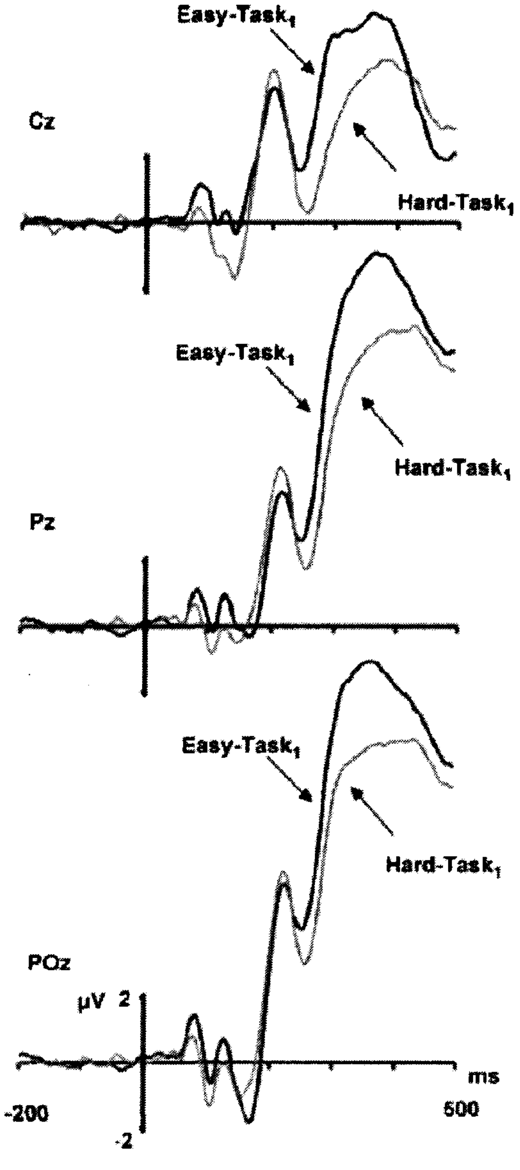

Easy-Task$_1$
Cz
Hard-Task$_1$
Easy-Task$_1$
Hard-Task$_1$
Pz
Easy-Task$_1$
Hard-Task$_1$
POz
µV 2
ms
-200
500
-2

Figure 7

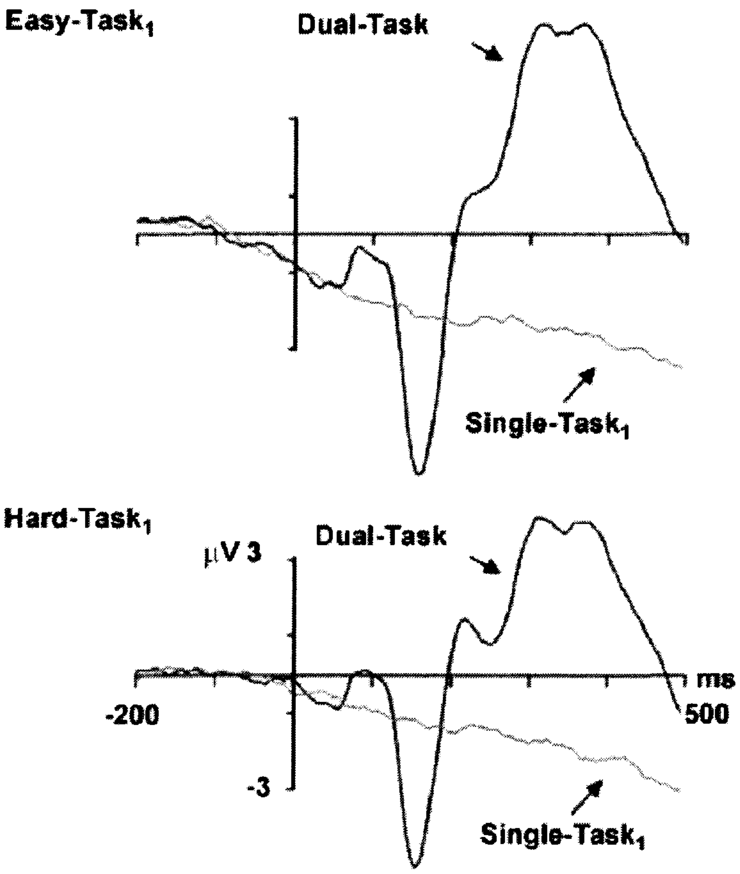

Easy-Task$_1$
Dual-Task
Single-Task$_1$
Hard-Task$_1$
µV 3
Dual-Task
ms
-200
500
-3
Single-Task$_1$

Figure 8

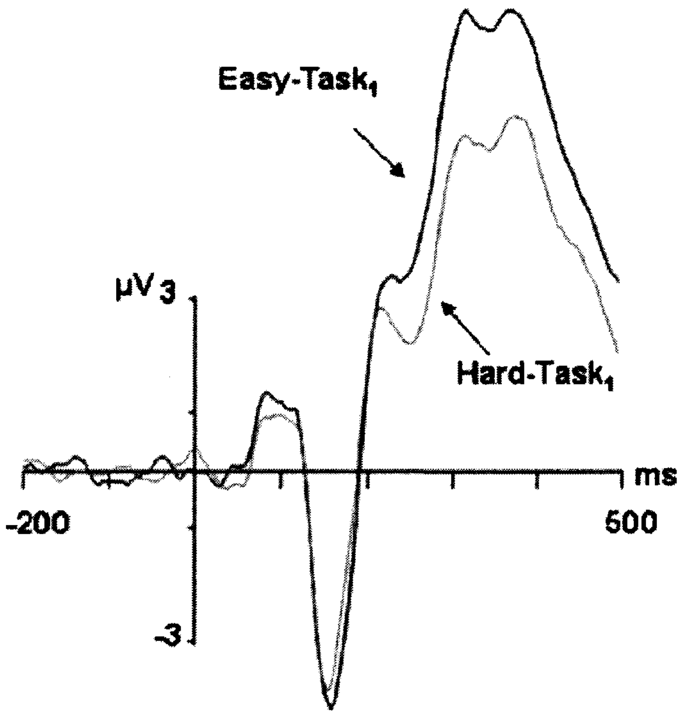
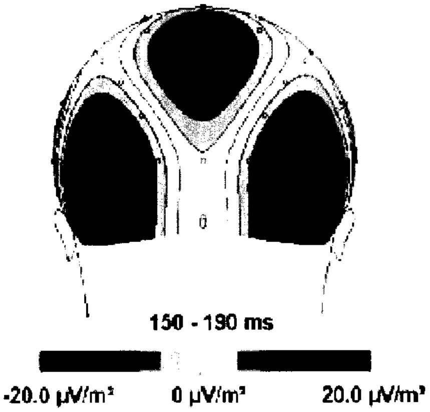
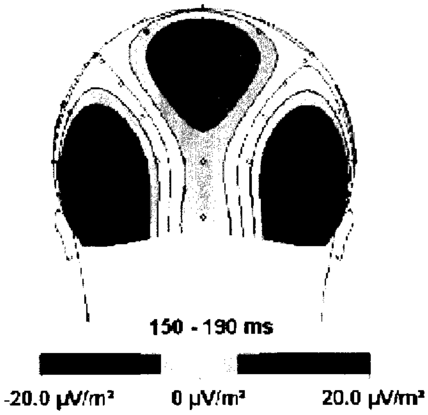


Figure 9

Easy-Task$_1$



Hard-Task$_1$



Easy-Task$_1$
minus
Hard-Task$_1$

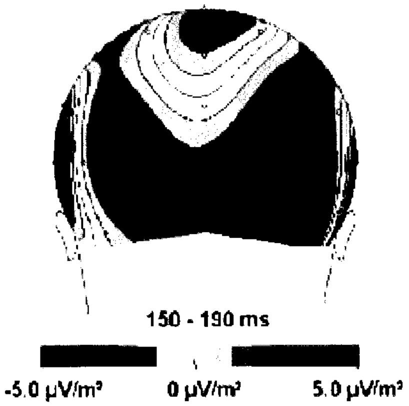
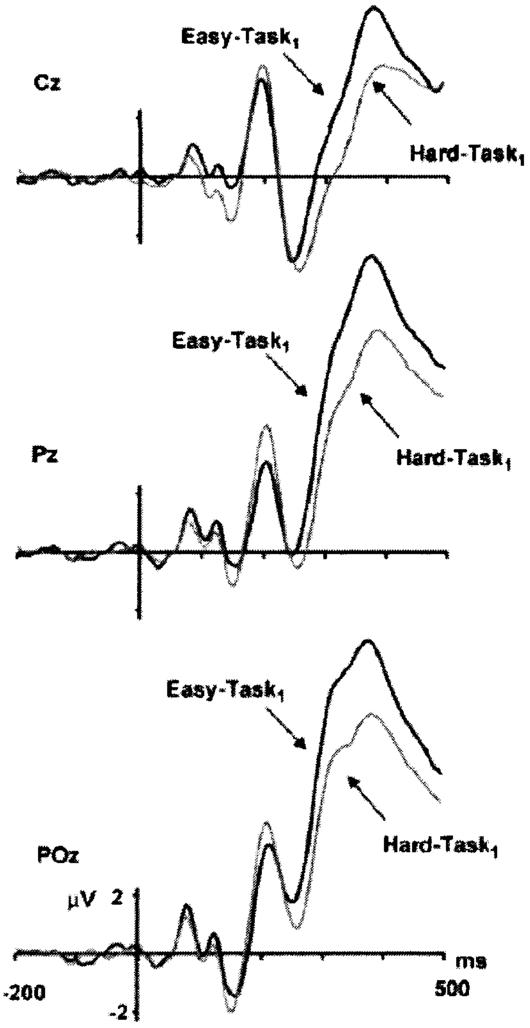


Figure 10


Cz
Easy-Task$_1$
Hard-Task$_1$
Pz
Easy-Task$_1$
Hard-Task$_1$
POz
Easy-Task$_1$
Hard-Task$_1$
µV 2
-2
-200
500
ms

General discussion

The studies included in the present thesis were designed to address two fundamental questions in attention research. The first question was whether central attention, which limits central processing in multiple task situations, interferes with visual-spatial attention, which enhances perceptual processing of attended items in the visual field. The second question was whether dual-task interference can take place prior to the central bottleneck.

Does central attention interfere with visual-spatial attention?

According to proponents of the central bottleneck model (Johnston, McCann, & Remington, 1995; Pashler, 1991), visual-spatial attention is independent from attention-limited central processing known to cause the PRP effect (i.e., the slowing of RT2 as SOA is reduced). In the General Introduction we argued that evidence for independence was inconclusive, and that further investigation was warranted, especially since others have claimed that central attention and visual-spatial attention might indeed share common mechanisms (e.g., Jiang & Chun, 2001).

Voluntary deployment of visual-spatial attention

To bring new evidence to bear on this issue, we recorded ERPs, and tracked the moment-by-moment deployment of visual-spatial attention by measuring the N2pc elicited by a lateralized visual target under different concurrent central load conditions manipulated using modified PRP paradigms.

In several experiments, we demonstrated that the N2pc component was attenuated when participants attempted to deploy visual-spatial attention voluntarily to a lateralized visual target while performing a capacity-demanding speeded auditory choice task (Articles 1, 2, and 4).

The observed N2pc attenuation was not caused by a failure of color perception *per se*, which is essential to locate the color-defined target toward which visual-spatial attention must be deployed, since the ability to locate a masked target-square in the visual display was not affected by central load, contrary to the ability to locate the gap in the masked target-square (see Article 1, control experiment). The absence of a laterality X Task 1-difficulty interaction in the N1 time-range (Article 4, Experiment 1) also suggests that pre-attentive relevant-feature detection processes necessary to locate the target were unaffected by concurrent processing of T1.

The N2pc results could not reflect visual capture either in these experiments, because the T1 was an auditory stimulus and T1 did not appear to come from a well localized point in space, but rather filled a large volume in the room. Any existing cross-modal spatial capture (McDonald & Ward, 2000) would have been equivalent in experiments that modulated concurrent central load by varying Task 1 difficulty without varying the SOA (Article 1, Experiment 2; Article 2, Task 1 difficulty manipulation; Article 4, Experiment 1).

Experiments with Task 1 difficulty manipulations also confirmed that the N2pc attenuation could not be due to ERP overlapping activity obscuring the N2pc. Indeed, in these experiments, SOAs were identical between Task 1 difficulty conditions, leading to identical sensory activity overlap between conditions. Moreover, greater Task 1 motor overlap in the N2pc time range would have been expected in easy-Task 1 conditions, where mean RT1 were shorter than in hard-Task 1 conditions. If overlapping activity obscured the N2pc, this should have led to opposite results than those observed, providing new empirical evidence to support the assumption that N2pc amplitude reductions are not caused by component overlap (further discussed in the Discussion section of Article 2).

Also, in all experiments where central load conditions were randomly presented within blocks, the differential attenuation of the N2pc was obtained in absence of any possible differential pre-trial preparatory state. As discussed extensively in the Discussion section of Article 2, we also convincingly demonstrated that N2pc modulations could be obtained in conditions were it was virtually impossible for participants to adapt their task preparation strategies dynamically after trial initiation.

The evidence presented in this thesis therefore unambiguously demonstrates that the all-or-none or capacity sharing bottleneck that is postulated to be responsible for the behavioral PRP effect is also responsible for the N2pc attenuation as task overlap increased in a paradigm where visual-spatial attention had to be deployed voluntarily on T2.

Given that the N2pc is considered a valid index of the locus of visual-spatial attention, it is safe to conclude that, contrary to what was assumed by proponents of the central bottleneck model (Johnston et al., 1995; Pashler, 1991) attention-limited central processing known to cause the PRP effect interferes with visual-spatial attention processes when visual-spatial attention is deployed voluntarily.

Recent studies have demonstrated that the N2pc was also attenuated in the AB paradigm (Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, Robitaille, 2006a, 2006b; Robitaille, Jolicœur, Dell'Acqua, & Sessa, 2007). The similarity of the interaction of central load on the N2pc mean amplitude when using PRP and AB paradigms provides more evidence in support of the central interference theory (Jolicœur, 1998, 1999a, 1999b) that postulates that response selection (assumed to be an important locus of the PRP effect) and short-term consolidation (postulated to be an important locus of the AB effect) have some overlap at the level of limited central mechanisms.

Although the N2pc attenuation by central load provides a clear-cut demonstrations of the interactions between central processing and visual-spatial attention, further work will be required to understand these interactions in more detail. This is because the specific visual-spatial attention processes indexed by the N2pc are still debated.

For example, recent studies have shown that N2pc latency and amplitude are not modulated by the prior knowledge of the visual hemifield in which the target will appear (Kiss, Van Velzen, & Eimer, 2008) nor by the validity of spatial cues in a predictive spatial cueing paradigm (Brisson & Jolicœur, 2008), suggesting that the N2pc reflects visual-spatial attention processes that occur after the displacement of the attentional locus *per se*. Indeed, if we take as an example the spatial cueing study conducted by Brisson and Jolicœur (2008), we would have expected that if the N2pc reflected (at least in part) the shift of attention to the target location, then its amplitude should have been attenuated in valid trials relative to invalid trials, since attention should have been at the correct location at target onset in valid trials, and therefore should not need to shift again in these trials, contrary to invalid trials.

Because the N2pc seems to occur after the displacement of attention, it is impossible to determine with the N2pc results observed in the present studies whether concurrent processing of the first auditory target interfered with the displacement of the attentional locus *per se*, or if the interference occurred only after attention was deployed to the target location, resulting in a failure to engage at the new location, since both types of interference would predict the observed attenuation of the N2pc.

Also, it has been suggested recently that the N2pc component reflected the summation of two distinct components: the P_D (for Distractor Positivity) and the N_T (for Target Negativity; Hickey, Di Lollo, & McDonald, 2008). It has been proposed that the P_D indexes distractor suppression processes given that it was elicited contralateral to the distractor, that it varied as a function of distractor position (and not as a function of target position), and that it arose from areas of the visual cortex that have been associated with spatial processing (dorsomedial cortex). The N_T, for its part, was elicited contralateral to the target, varied as a function of target position (but not of distractor position), and arose from areas of the visual cortex that have been associated with the processing of object identity (ventrolateral cortex), leading the authors to postulate that it indexes target processing. Further studies will need to be conducted to determine whether central attention selectively interferes with only one of these two components, or with both.

Involuntary contingent capture of visual-spatial attention

As mentioned in the General Introduction, visual-spatial attention can be deployed voluntarily or involuntarily. Voluntary and involuntary deployments of attention have different time courses (Jonides, 1981; Müller & Rabbitt, 1989), indicating that the mechanisms that control them may be different. Therefore, it is possible that central attention interferes with visual-spatial attention only when it is deployed voluntarily.

To investigate if central attention also interfered with involuntary deployments of visual-spatial attention, we employed the same logic as in the preceding experiment. However, instead of incorporating a visual search task as the second task of an audio-visual PRP paradigm, and measuring the N2pc elicited by the lateralized visual ***target*** in different concurrent central load conditions, we incorporated a contingent capture task, namely the one used in Leblanc et al. (2008; Experiment 4), and measured the N2pc elicited by the lateralized visual task-irrelevant ***distractor*** that matched the top-down attentional control settings of the observers in different concurrent central load conditions. Central load was manipulated by varying SOA, and the SOAs (200 ms and 500 ms) were chosen so that the distractor display would appear well before the response in Task 1, minimizing the possibility of differential task preparation.

As in Leblanc et al. (2008), the target-colored distractors elicited a significant N2pc wave whereas nontarget-colored distractors did not, indicating that visual-spatial attention had been involuntarily drawn to the target-colored distractor location, but not to the nontarget-colored distractor location, demonstrating once again a visual-spatial locus of contingent capture. Importantly, the N2pc elicited by the target-colored distractor was attenuated at the short SOA, suggesting that the allocation of central resources to a concurrent demanding speeded auditory task interfered with the involuntary deployment of visual-spatial attention that occurs during contingent capture.

As mentioned in the Discussion of Article 3, further research is required to determine whether the central bottleneck interfered directly with involuntary visual-spatial attention processes (i.e., the deployment or engagement of visual-spatial attention) or whether devoting central processing to T1 made it more difficult concurrently to maintain the top-down settings for T2, or whether it was a combination of the above. The fact that central processing does not seem to interfere with pre-attentive relevant feature detection of a target presented concurrently with only one distractor (Article 4, Experiment 1) suggests that top-down settings could be maintained while central processes are occupied on a first target. However, other studies suggest that concurrent central processing does not interfere with the involuntary deployment of visual-spatial attention when captured by an external event is not dependant on top-down settings. For example, Ghorashi, Di Lollo, and Klein (2007) have reported that peripheral transient cues are as effective during and outside the AB, and Pashler (1991) failed to observe a significant SOA effect on report accuracy for T2 when a peripheral onset cue indicated the location of T2 (Experiment 1: 1.9%; $p > .20$). These last two studies report the absence of an effect, however. Caution is therefore required as to the conclusions they inspire.

Does dual-task interference occur prior to the central bottleneck?

An influential model of PRP interference, the central bottleneck model (e.g., McCann & Johnston, 1992; Pashler, 1994; Pashler & Johnston, 1989; Welford, 1952), postulates that central processes, such as response selection and decision making, cannot operate concurrently on more than one target, and thus act as a processing bottleneck. Perceptual processes that lead to stimulus identification (and response execution processes that lead to the overt response), on the other hand, can operate in both tasks in parallel, without interference, and can proceed simultaneously with the central bottleneck stage(s). Although some aspects of this model have been contested (see General Introduction for more details), the idea that interference starts to occur after perceptual processing is completed is widely accepted.

However, there is mounting evidence, including the N2pc attenuation reported above, that suggests that interference may begin to occur at a perceptual level of processing, at least when difficult perceptual discriminations are involved. A careful examination of the time course of interference in the PRP paradigm was therefore warranted.

SPCN

We first examined a newly discovered ERP component that indexes visual short-term memory retention processes, the sustained posterior contralateral negativity (SPCN: Jolicœur et al., 2008; Klaver et al., 1999; McCollough et al., 2007; Perron et al., 2008; Vogel & Machizawa, 2004).

In several experiments (e.g., Articles 2 and 4), we observed a progressive lengthening of the SPCN onset latency as overlap increased between the first auditory task and the second visual task, suggesting that the transfer into visual short-term memory was delayed by concurrent central processing. In all cases, the increase in SPCN latency was only a fraction of the PRP effect, however, suggesting that dual-task interference in the PRP paradigm is dominated by central postponement. Nevertheless, the substantial increase in the latency of the SPCN is an important result, because it is the first demonstrations that modality-specific visual encoding processing (e.g., consolidation in visual short-term memory) can be delayed by a demanding concurrent speeded auditory task. Interestingly, in the AB paradigm, where dual-task interference is reflected by a decrease in T2 report accuracy, the SPCN is also sharply attenuated (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b, Robitaille et al., 2007), suggesting that the SPCN, and therefore visual short-term memory activity, seems to be a good predictor of conscious report. The lengthening of the SPCN onset latency observed in the present studies therefore suggest that encoding a visual representation in a format that supports conscious report is delayed significantly by cross-modal multitasking.

Although delayed, the SPCN finally reached similar amplitudes across task overlap conditions in all experiments, suggesting that a stable visual short-term memory representation could eventually be achieved in all central load conditions, which is consistent with the high accuracy of report of T2 that is usually observed in PRP studies when T2 is not masked.

The different patterns of N2pc modulations (amplitude attenuation) and SPCN modulations (delay of the onset latency) not only provided further evidence that the N2pc and SPCN components index different visual processes with different functions (see Jolicœur et al., 2008), but also provide important potential insights in the nature of attentional limitations.

Pashler (1989) proposed a two-component theory that postulates the existence of two separate and qualitatively different types of attentional limitations: 1) visual attention limits, which have resource-like properties and arise when multiple visual stimuli are presented simultaneously, and 2) central attention limits, which have bottleneck-like properties and arise in dual-task conditions. The attenuation of the N2pc by central load refutes the claim that visual attention and central attention are completely separate. However, the attenuation of the N2pc combined with the delay of the SPCN seems to support the claim that there are (at least) two qualitatively different types of attention, one that constrains processing before consolidation in visual short-term memory, in a capacity-sharing manner, and one that constrains processing at/after consolidation in visual short-term memory, in a bottleneck manner.

Visual P1 and occipital N1

The N2pc and SPCN results provided new upper bounds of dual-task interference in the PRP paradigm. The next step was to investigate earlier components, such as the visual P1 and occipital N1. This was done in Article 4.

In the three first studies, the computation of the contralateral minus ipsilateral difference wave to isolate the N2pc and SPCN eliminated overlapping activity that was not lateralized with respect to the location of T2, including Task 1 activity. However, in order to measure the visual P1 and occipital N1 elicited by T2, we had to adopt a different strategy to isolate Task 2 ERPs from overlapping Task 1 ERPs in the fourth study. We used the same four tones as in the preceding experiments, but this time took advantage of a built-in manipulation of Task 1 difficulty. It has been demonstrated that when four tone frequencies arrayed from low to high are mapped to four response keys arrayed from left to right, the mean response times to the highest and lowest frequencies are shorter than those of the middle frequencies. The highest and lowest frequencies were included in the easy-Task 1 condition and the two middle tones were included in the hard-Task 1 condition. Furthermore, the T1-T2 SOA was adjusted dynamically so that T2 would be presented usually after the response to T1 in the easy-Task 1 condition, but before the response to T1 in the hard-Task 1 condition. This enabled us to vary task overlap randomly in each block (which was maximized in the hard-Task 1 condition and minimized in the easy-Task 1 condition) while using identical SOAs in both Task 1 conditions. Finally, we included single-Task 1 trials in which only T1 was presented. These single-Task 1 trials, randomly intermixed with dual-task trials, were identical to the dual-task trials, except that T2 was not presented and therefore no associated Task 2 processing was required. By computing the average EEG activity time-locked to T1 onset + SOA (the time at which T2 would have been presented) in these trials, we were able to estimate overlapping Task 1 activity, which we then subtracted from theT2-locked (i.e., T1 onset + SOA) dual-task ERPs, thus isolating the ERP associated to T2 processing (see Article 4 for a discussion on the validity of this novel subtraction method).

The first objective of this study was to determine the time course of interference when T2 was associated to a discrimination task (Study 4; Experiment 1). The visual display that contained T2 was similar to the one used in the three first experiments with the exception that here the lateralized target was presented with only one distractor in the opposite hemifield.

Again, the attenuation of the N2pc was followed by a delay in the SPCN onset latency. Importantly, these effects were preceded by an attenuation of the hard-Task 1 waveform compared to the easy-Task 1 ERP waveform in the occipital N1 (150-190 ms post-T2) and visual P1 (100-120 ms post-T2) time range. These effects of Task 1 difficulty are the earliest dual-task interference effects ever reported in the context of the PRP paradigm, and the fact that they occurred over the occipital (visual) cortex provide strong evidence that cross-modal multitasking interference starts to occur prior to central, amodal processing.

It is also important to mention that the observed interference in the P1 and N1 time ranges do not contradict the claim that delays of Task 2 central processes are the main cause of the PRP effect. The results strongly suggest, however, that extant theories should be extended to acknowledge the existence of interference in perceptual processing in cross-modal multitasking paradigms, at least under some conditions.

The speeded auditory task did not seem to interfere with all visual processes, however. For example, the fact that the occipital N1 was larger contralateral than ipsilateral to T2, but that this effect of laterality was not modulated by the Task 1 difficulty manipulation, suggested that concurrent Task 1 processing did not interfere with feature detection processes (see Hopf et al., 2004). So what are the specific visual processes that are affected by cross-modal multitasking?

Because the occipital N1 is sensitive to visual discriminative processes (Vogel & Luck, 2000), the natural first step we took to investigate this last question was to determine the time course of interference when T2 was associated to a detection task, instead of a discrimination task. In these conditions, the first significant effect that we observed was in the second half of the occipital N1 (170-190 ms), and this effect was smaller than when T2 was associated to a discrimination task. These N1 results are important, because they reveal that dual-task interference on perceptual processing also occurs when easy, simple T2 detection is required. Moreover, in combination with the N1 results when T2 was associated to a discrimination task, the present results support the hypothesis that the speeded auditory task interfered specifically with visual discriminative processes. If we assume that some visual discriminative processes are still required in detection tasks, because a detection task requires the observer to discriminate between the presence and absence of a stimulus, then we could assume that the effect of dual-task interference on the occipital N1 entirely reflects a modulation of discriminative processing. However, it is also possible that part of the dual-task interference observed on the amplitude of the N1 in both experiments of Article 4 reflects a more general aspect of visual processing. For example, because the auditory T1 always preceded the visual T2, it is possible that participants preferentially prepared the auditory cortex to receive T1, and then, at some point after T1 onset, prepared the visual cortex to receive T2. It is possible that the time course of this modality-switch could be affected by task overlap, and that it occurred later in the hard-Task 1 condition than in the easy-Task 1 condition, which would explain the small N1 effect observed in Experiment 2 of Article 4. If this was true, however, we could expect that the visual P1 would also be attenuated in Experiment 2, which was not the case (the tendency was not statistically significant).

Given the presence of a visual P1 effect in Experiment 1, it is hard to explain the absence of an effect on this component in Experiment 2. However, a tentative explanation could be provided by the fact that the visual P1 has been shown to be sensitive to different states of arousal (Vogel & Luck, 2000). It is possible that the P1 arousal effect is caused by top-down inputs in the visual cortex similar to the sensory gain control processes thought to be reflected in the P1 attention effect (Hillyard, Luck, Vogel, 1998). If concurrent processing interferes with the processes underlying the P1 arousal effect, then we could expect to find an effect of Task 1 difficulty on P1 amplitude when T2 is associated to a harder discrimination task, but not if it is associated to an easier detection task.

In this thesis, I argued in favour of a central interference theory (Jolicœur, 1998, 1999a, 1999b) that states that attentional mechanisms stressed in PRP and AB paradigms are not independant. Up to here, all the results we presented were coherent with such a claim, including the multitasking interference on the N2pc and SPCN components found in both

AB (Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b; Robitaille et al., 2007) and PRP studies (all articles included in the present thesis). So why, assuming that the central interference theory is correct, do we observe P1/N1 effects in the present PRP experiments when previous AB studies (e.g., Vogel et al., 1998) failed to observe such effects?

One direct explanation is tied to the fact that Vogel and al. (1998) used a subtraction method that isolated the ERPs elicited by an irrelevant probe that surrounded T2, whereas here we developed a subtraction method that isolated ERPs elicited by T2 directly. The absence of an effect of central attention on the visual P1/N1 in Vogel et al.'s AB study, combined with the presence of an effect in our study, could therefore indicate simply that central attention interferes mainly with active perceptual processing of T2, and not with passive perceptual activity elicited by any relevant or irrelevant visual items. This account is supported by a recent AB study by Reiss and colleagues (Reiss, Hoffman, Heyward, Doran, & Most, 2008), which observed a reduction of the T2-locked selection negativity (SN) as task overlap increased (i.e., as T1-T2 SOA decreased). The SN is thought to index the discrimination and selection of a feature or feature conjunction that is selectively processed according to its task relevance (Hillyard & Anllo-Vento, 1998). It is an occipital ERP component that starts about 140-180 ms after the onset of a visual stimulus and lasts about 200 ms.

Although the last hypothesis seems sufficient to explain the apparent discrepancies between the AB and PRP studies, other possible explanations will deserve further investigation. One is related to the fact that T2 was presented at fixation in the AB studies whereas T2 was presented in the periphery in our PRP studies. Handy and Khoe (2005) have shown that early ERP effects of visual-spatial attention in spatial cueing paradigms were present when the target was presented in the periphery, but disappeared when the target was presented at fixation. These results were explained by the fact that visual acuity is greater at fixation than in the periphery, and therefore the advantage of increasing visual acuity through attention related sensory gain control mechanisms is reduced when the target is presented at fixation. If the P1/N1 effects observed in our studies reflected some kind of interference of central attention on visual-spatial attention, then we could also expect differences of central attention effects on the P1/N1 components when T2 is presented at fixation or in the periphery.

Another interesting hypothesis is based on the fact that in the AB studies, both T1 and T2 were visual, whereas we used an auditory T1 and a visual T2. It is therefore possible that central interference on the P1/N1 components depend on a modality switch. If this is the case, it would be an important finding, given that it would contradict the assumption that presenting T1 and T2 in different modalities reduces potential perceptual interference because it reduces perceptual load, an assumption that led many researchers to adopt cross-modal paradigms in PRP studies.

Conclusion

The results reported in this thesis do not contradict the proposal that a bottleneck at the level of response selection/decision making is the major underlying cause of the PRP effect (see Pashler, 1994 for a review). However, as postulated by the central interference theory (Jolicœur, 1998, 1999a, 1999b), the results suggest that the central bottleneck encompasses other central processes, such as short-term consolidation (Jolicœur & Dell'Acqua, 1998), and even modality-specific processes, such as consolidation into visual short-term memory (see also Stevanovski & Jolicœur, 2006). In fact, the present studies suggest that visual short-term memory consolidation, as reflected by the onset latency of the SPCN, is the first process which is delayed in the PRP paradigm, and therefore is likely the first process subjected to serial processing under dual-task conditions.

Our results also strongly suggest that the central bottleneck is not the only attentional limit that manifests itself in the cross-modal PRP paradigm, as suggested by many extant theories of dual-task interference (Navon & Miller, 2002; Meyer & Kieras, 1997; Pashler, 1994; Tombu & Jolicœur, 2003). Indeed, the attenuation of the N2pc, of the occipital N1 and of the visual P1 under high task overlap conditions support the hypothesis that bottleneck-like central attention limits interact with capacity-like visual attention limits. The existence of two types of attentional limits that possess different properties has been put forward in the two-component theory (Pashler, 1989). However, unlike the two-component theory, which postulates that these two types of attention are independent (see also Pashler, 1991; Johnston, McCann, & Remington, 1995), I propose that they are not. In addition, unlike the two-component theory, which assumes that only central attention limits are taxed in the PRP paradigm, I propose that the two types of attention are implicated in PRP dual-task limitations. That is, when central attention is focused on Task 1, visual attention, which increases perceptual processing of T2, is less efficient.

It is further suggested that engaging central attention on an auditory Task 1 interfered with specific visual processes in Task 2, including visual discriminative processes, consolidation into visual short-term memory, and possibly the processes underlying P1 arousal effects. However, task-relevant feature detection seemed to be independent of task overlap, which is coherent with the proposal that central attention interferes with visual attention, and that feature detection is a pre-attentive process.

Interestingly, the amplitude of the SPCN seems to be positively correlated to conscious report (Article 2; Dell'Acqua et al., 2006; Jolicœur et al., 2006a, 2006b; Woodman & Luck, 2003b), whereas earlier components, such as the N2pc, are not (Article 2; Woodman & Luck, 2003b). Therefore, our results not only suggest for the first time that access to consciousness is delayed under multitasking conditions in the PRP paradigm, but also suggest that "unconscious" processing is under the control of a different type of attention than "conscious" processing.

References

Arnell, K. M. (2006). Visual, auditory, and cross-modality dual-task costs: Electrophysiological evidence for an amodal bottleneck on working memory consolidation. *Perception & Psychophysics*, 68, 447-457.

Arnell, K. M., Helion, A. M., Hurdelbrink, J. A., & Pasieka, B. (2004). Dissociating sources of dual-task interference using human electrophysiology. *Psychonomic Bulletin & Review*, 11, 77-83.

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics, 55*(5), 485-496.

Brisson, B., & Jolicœur, P. (2008). *Express attentional re-engagement but delayed entry into consciousness following invalid spatial cues.* Manuscript submitted for publication. Département de psychologie, Université de Montréal, Montréal, Québec, Canada.

Brisson, B., & Jolicœur, P. (2007). The N2pc component and stimulus duration. *NeuroReport*, 18, 1163-1166.

Brisson, B., Robitaille, N., & Jolicœur, P. (2007). Stimulus intensity affects the latency but not the amplitude of the N2pc. *NeuroReport, 18*, 1627-1630.

Carrier, M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 1339-1348.

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.

Cohen, A., & Ivry, R.B. (1991). Density effects in conjunction search: evidence for a coarse location mechanism of feature integration. *Journal of Experimental Psychology: Human Perception & Performance*, 17, 891-901.

Coles, M.G. (1989) Modern mind-brain reading: psychophysiology, physiology, and cognition. *Psychophysiology*, 26, 251-69.

De Beaumont, L., Brisson, B., Lassonde, M., & Jolicœur, P. (2007) Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain Injury, 21,* 631-644.

de Fockert, J.W., Rees, G., Frith, C.D., & Lavie, N. (2001). The role of working memory in visual selective attention. *Science*, 291, 1803-1806.

Dell'Acqua, R., & Jolicœur, P. (2000). Visual encoding of patterns is subject to dual-task interference. *Memory & Cognition*, 28, 184-191.

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

Dell'Acqua, R., Jolicœur, P., Vespignani, F., & Toffanin, P. (2005). Central processing overlap modulates P3 latency. *Experimental Brain Research*, 165, 54-68.

Dell'Acqua, R., Pascali, A., & Peressotti, F. (2000). Modulazione di una variabile percettiva in un contesto di doppio-compito. *Giornale Italiano di Psicologia*, 27, 843-848.

Dell'Acqua, R., Pesciarelli, F., Jolicœur, P., Eimer, M., & Peressotti, F. (2007). The interdependence of spatial attention and lexical access as revealed by early asymmetries in occipito-parietal ERP activity. *Psychophysiology*, 44, 436-443.

Dell'Acqua, R., Sessa, P., Jolicœur, P., & Robitaille, N. (2006). Spatial attention freezes during the attention blink. *Psychophysiology*, 43, 394-400.

Di Russo, F., Martinez, A., & Hillyard, S.A. (2003). Source analysis of event-related cortical activity during visuo-spatial attention. *Cerebral Cortex 13*, 486-499, 2003.

Downing, P.E. (2000). Interactions between visual working memory and selective attention. *Psychological science*, 11, 467-473.

Drew, T., & Vogel, E.K., (2008). Neural measures of individual differences in selecting and tracking multiple moving objects. *Journal of Neuroscience*, 28, 4183-4191.

Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. *Psychological Review*, 96, 433-458.

Donchin, E. (1981). Surprise!... Surprise? *Psychophysiology*, 18, 493-513.

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

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience*. In press.

Eimer, M., & Mazza, V. (2005). Electrophysiological correlates of change detection. *Psychophysiology*, 42, 328-342.

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

Folk, C. L., & Remington, R. W. (1998). Selectivity in distraction by irrelevant featural singletons: Evidence for two forms of attentional capture. ***Journal of Experimental Psychology: Human Perception and Performance***, 24, 847-858.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: Contingent attentional capture by apparent motion, abrupt onset, and color. ***Journal of Experimental Psychology: Human Perception and Performance***, 20, 317-329.

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.

Handy, T.C., & Khoe, W. (2005). Attention and sensory gain control: a peripheral visual process? Journal of Cognitive Neuroscience, 17, 1936-1949

Hawkins, H.L., Shafto, M.G., & Richardson, K. (1988). Effects of target luminance and cue validity on the latency of visual detection. ***Perception & Psychophysics***, 44, 484-492.

Hickey, C., Di Lollo, V., & McDonald, J.J. (2008). Electrophysiological Indices of Target and Distractor Processing in Visual Search. ***Journal of Cognitive Neuroscience.*** In press.

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. ***Journal of Cognitive Neuroscience*, *18***(4), 604-613.

Hillyard, S.A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. ***Proceedings of the National Academy of Sciences***, 95, 781-787.

Hillyard, S.A. & Picton. T.W. (1987). Electrophysiology of cognition. In: F. Plum (Ed.). Handbook of Physiology Section 1: The Nervous System. Volume V. Higher Functions of the Brain, Part 2. Bethesda, Maryland: American Physiological Society. pp. 519-584.

Hillyard, S. A., Vogel, E. K., & Luck, S. J. (1998). Sensory gain control (amplification) as a mechanism of selective attention: Electrophysiological and neuroimaging evidence. ***Philosophical Transactions of the Royal Society: Biological Sciences***, 393, 1257-1270.

Hopfinger, J.B., & Mangun, G.R. (1998). Reflexive attention modulates processing of visual stimuli in humain extratriate cortex. ***Psychological Science***, 9, 441-447.

Hopfinger, J.B., & Mangun, G.R. (2001).Tracking the influence of reflexive attention on sensory and cognitive processing. Cognitive, Affective, and Behavioural Neuroscience, 1, 56-65.

Ghorashi, S.M.S., Di Lollo, V., Klein, R.M. (2007). Attentional orienting in response to peripheral cues survives the attentional blink. ***Visual Cognition***, 15, 87-90.

Jaśkowski, P., van der Lubbe, R.H., Schlotterbeck, E., & Verleger, R. (2002). Traces left on visual selective attention by stimuli that are not consciously identified. ***Psychological Science***, 13, 48-54.

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

Johnston, J.C., McCann, R.S., & Remington, R.W. (1995). Chronometric evidence for two types of attention. ***Psychological Science***, 6, 365-369.

Jolicœur, P. (1998). Modulation of the attentional blink by on-line response selection: Evidence from speeded and unspeeded Task1 decisions. ***Memory & Cognition***, 26, 1014-1032.

Jolicœur, P. (1999a). Dual-task interference and visual incoding. ***Journal of Experimental Psychology: Human Perception and Performance***, 25, 596-616.

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

Jolicœur, P., Brisson, B., Robitaille, N. (2008). Dissociation of the N2pc and sustained posterior contralateral negativity in a choice response task. ***Brain Research***, 1215C: 160-172.

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

Jolicœur, P. (1999a). Dual-task interference and visual incoding. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 596-616.

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

Jolicœur, P., Dell'Acqua, R., & Crebolder, J. (2001). The attentional blink bottleneck. In K. Shapiro (Ed.), The Limits of Attention: Temporal Constraints on Human Information Processing (pp. 82-99). New York: Oxford University Press.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006a). Attentional control and capture in the attentional blink paradigm: Evidence from human electrophysiology. *European Journal of Cognitive Psychology*, 18, 560-578.

Jolicœur, P., Sessa, P., Dell'Acqua, R., & Robitaille, N. (2006b). On the control of visual spatial attention. *Psychological Research*, 70, 414-424.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J.B. Long & A.D. Baddeley (Eds.), *Attention and performance IX*, (pp.187-203). Hillsdale, NJ: Erlbaum.

Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology*, 20, 167-178.

Kiss, M., Goolsby, B.A., Raymond, J.E., Shapiro, K.L., Silvert, L., Nobre, A.C., Fragopanagos, N., Taylor, J.G. & Eimer, M. (2007). Efficient attentional selection predicts distractor devaluation: Event-related potential evidence for a direct link between attention and emotion. *Journal of Cognitive Neuroscience*, 19, 1316-1322.

Kiss, M., Jolicœur, P., Dell'Acqua, R., & Eimer, M. (2008). Attentional capture by visual singletons is mediated by top-down task-set: New evidence from the N2pc component. Psychophysiology. In press.

Kiss, M., van Velzen, J., & Eimer, M. (2008). The N2pc component and its links to attention shifts and spatially selective visual processing. *Psychophysiology*, 45: 240–249.

Klaver, P., Talsa, 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.

Kutas, M., & Hillyard S.A. (1980). Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science*, 207, 203-205.

Lamy, D., Leber, A. B., & Egeth, H. E. (2004). Effects of task relevance and stimulus-driven salience in feature-search mode. *Journal of Experimental Psychology: Human Perception and Performance*, 30, 1019-1031.

Lavie, N., Hirst, A., de Fockert, J.W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133*, 339-354.

Leblanc, É., & Jolicœur, P. (2005). The time course of the contingent spatial blink. *Canadian Journal of Experimental Psychology*, 59, 124-131.

Leblanc, É., Prime, D., & Jolicœur (2008). Tracking the location of visuospatial attention in a contingent capture paradigm. ***Journal of Cognitive Neuroscience***, 20, 657-671.

Lien, M.-C., Ruthruff, E., Goodin, Z., & Remington, R. W. (2008). Contingent attentional capture by top-down control settings: Converging evidence from event-related potentials. ***Journal of Experimental Psychology: Human Perception and Performance, 34,*** 509-530.

Lorenzo-López, L., Amenedo, E., & Cadaveira, F. (2008). Feature processing during visual search in normal aging: electrophysiological evidence. ***Neurobiology of*** Aging, 29, 1101-1110.

Luck, S.J. (1998). Sources of dual-task interference: evidence from human electrophysiology. ***Psychological Science***, 9, 223-227.

Luck, S.J. (2005). ***An introduction to the event-related potential technique***. Cambridge MA: The MIT press.

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., Fuller, R.L., Braun, E.L., Robinson, B., Summerfelt, A., & Gold, J.M. (2006). The speed of visual attention in schizophrenia: electrophysiological and behavioral evidence. ***Schizophrania Research***, 85, 174-195.

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

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

Luck, S. J., & Hillyard, S. A. (1994b). Electrophysiological correlates of feature analysis during visual search. ***Psychophysiology***, 31, 291-308.

Luck, S. J. & Vecera, S. P. (2002). Attention. In H. Pashler (Series Ed.) & S. Yantis (Volume Ed.), Stevens' Handbook of Experimental Psychology: Vol. 1. Sensation and Perception (3rd ed., pp. 235-286).

Luck, S. J., Vogel, E. K., & Shapiro, K. L. (1996). Word meanings are accessed but cannot be reported during the attentional blink. ***Nature***, 383, 616-618.

Magliero, A., Bashore, T.R., Coles, M.G. H.,& Donchin, E. (1984). On the dependence of P300 latency on stimulus evaluation processes. ***Psychophysiology***, 21, 171-186.

Mangun, G.R. (1995) Neural mechanisms of visual selective attention. ***Psychophysiology***, 32, 4-18.

Mangun, G.R., & Hillyard, S.A. (1991). Modulation of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. ***Journal of Experimental Psychology: Human Perception and Performance***, 17, 1057-1074.

McCann, R.S., & Johnston, J.C. (1992). Locus of the single-channel bottleneck in dual-task interference. ***Journal of Experimental Psychology: Human Perception and Performance***, 18, 471-484.

McCollough, A.W., Machizawa, M.G., & Vogel, E.K. (2007) Electrophysiological measures of maintaining representations in visual working memory. ***Cortex***, 43, 77-94.

McDonald, J.J., Hickey, C., Green, J.J., & Whitman, J.C. (2008). Inhibition of Return in the Covert Deployment of Attention: Evidence from Human Electrophysiology.***Journal of Cognitive Neuroscience***. In press.

McDonald, J.J., & Ward, L.M. (2000). Involuntary listening aids seeing: evidence from human electrophysiology. ***Psychological Science***, 11, 167-171.

Meyer, D.E., & Kieras, D.E. (1997). A computational theory of executive cognitive processes and human multiple-task performance: Part 2. Accounts of psychological refractory-period phenomena. ***Psychological Review***, 104, 749-791.

Müller, H.J., & Rabbitt, P.M.A. (1989). Reflexive and voluntary orienting of attention: time course of activation and resistance to interruption. ***Journal of Experimental Psychology: Human Perception and Performance***, 15, 315-330.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of single bottleneck notion. Cognitive Psychology, 44, 193-251.

Oriet, C., & Jolicœur, P. (2003). Absence of perceptual processing during reconfiguration of task-set. ***Journal of Experimental Psychology: Human Perception and Performance***, 29, 1036-1049.

Osman, A., & Moore, C.M. (1993). The locus of dual-task-interference: Psychological refractory effects on movement-related brain potentials. ***Journal of Experimental Psychology: Human Perception and Performance***, 19, 1292-1312.

Palmer, J., Verghese, P., & Pavel, M. (2000). The psychophysics of visual search. ***Vision Research***, 40, 1227-1268.

Pashler, H. (1984). Processing stages in overlapping tasks: evidence for a central bottleneck. ***Journal of Experimental Psychology: Human Perception and Performance***, 10, 358-377.

Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: evidence for a two-component theory of divided attention in simple tasks. ***Cogitive Psychology***, 21, 469-514.

Pashler, H. (1991). Shifting visual attention and selecting motor responses: distinct attentional mechanisms. ***Journal of Experimental Psychology: Human Perception and Performance***, 17, 1023-1040.

Pashler, H. (1994). Dual-task interference in simple tasks: data and theory. ***Psychological Bulletin***, 116, 220-244.

Pashler, H., & Christian, C.L. (1994). Bottlenecks in planning and producing vocal, manual and foot responses (Center for Human Information Processing Technical Report). La Jolla, CA: University of

California, San Diego, Center for Human Information Processing. (Available from http://www.pashler.com/manuscripts.html)

Pashler, H., & Johnston, J.C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. ***Quarterly Journal of Experimental Psychology***, 41A, 19-45.

Perron R, Lefebvre C, Robitaille N, Brisson B, Gosselin F, Arguin M, Jolicœur P (2008) Attentional and anatomical considerations for the representation of simple stimuli in visual short-term memory: Evidence from human electrophysiology. ***Psychological Research***. In press.

Predovan, D., Prime, D., Arguin, M., Gosselin, F., Dell'Acqua, R., & Jolicœur, P. (2008). On the representation of words and nonwords in visual short-term memory: Evidence from human electrophysiology. ***Psychophysiology***. In press.

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

Ptito, A., Arnell, K., Jolicœur, P., & MacLeod, J. (2008). Intramodal and crossmodal processing delays in the attentional blink paradigm revealed by event-related potentials. ***Psychophysiology***. In press.

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.

Reiss, Hoffman, Heyward, Doran, & Most (2008). ERP evidence for temporary loss of control during the attentional blink. Poster presented at the Vision Sciences Society Annual Meeting. Naples, Florida, USA, May 9-14, 2008.

Ritter, W., Simson, R., Vaughan, H.G. Jr., Friedman, D.A. (1979). Brain event related to the making of a sensory discrimination. ***Science***, 203,1358-61.

Robitaille, N., & Jolicœur, P. (2006). Fundamental properties of the N2pc as an index of spatial attention: effect of masking. ***Canadian Journal of Experimental Psychology***, 60, 101-111.

Robitaille, N., Jolicœur, P., Dell'Acqua, R., Sessa, P. (2007). Short-term consolidation of visual patterns interferes with visuo-spatial attention: converging evidence from human electrophysiology. ***Brain Research***, 1185, 158-69.

Rolke, B., Heil, M., Streb, J., & Hennighausen. E. (2001). Missed prime words within the attentional blink evoke an N400 semantic priming effect. ***Psychophysiology***, 38, 165-174.

Ruthruff, E., Miller, J., & Lachmann, T. (1995). Does mental rotation require central mechanisms? ***Journal of Experimental Psychology: Human Perception and Performance***, 21, 552-570.

Ruthruff, E., Pashler, H.E. (2001). Perceptual and central interference in dual-task performance. In Kimron Shapiro (Ed.), ***Temporal Constraints on Human Information Processing***. Oxford University Press.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. ***Journal of***

Experimental Psychology: Human Perception and Performance, *25*, 408-425.

Schweickert, R. (1980). Critical-path scheduling of mental processes in a dual-task. *Science*, 209, 704-706.

Sergent, C., Baillet, S., & Dehaene, S. (2005).Timing of the brain events underlying access to consciousness during the attentional blink. ***Nature Neuroscience***, 10, 1391-400.

Shaw, M.L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 109-122). Hillsdale, NJ: Erlbaum.

Sommer, W., Leuthold, H,. & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. *Psychonomic Bulletin & Review*, 8, 81-88.

Stevanovski, B., & Jolicœur, P. (2006). Visual short-term memory: Central capacity limitations in short-term consolidation. *Visual Cognition*, 15, 532-563.

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, 14, 1-36.

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., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 15-48.

Ulrich R, Fernández, S.R., Jentzsch, I., Rolke, B., Schröter, H., & Leuthold H. (2006). Motor limitation in dual-task processing under ballistic movement conditions.Psychological Science, 17, 788-793.

Van Selst, M., & Johnston, J.C. (1996, November). Dual-task interference that cannot be attributed to output interference. Paper presented at the 37th Annual Meeting of the Psychonomics Society, Chicago.

Van Selst, M., & Jolicœur, P. (1997). Decision and response in dual-task interference. *Cognitive Psychology*, 33, 266-307.

Verlegger, R. (1988). Event related potentials and cognition: a critique of the context updating hypothesis and an alternative interpretation of the P3. *Behavioral Brain Science*, 11, 343-427.

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., & Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology*, 37, 190-203.

Vogel, E.K., & Luck, S.J. (2002). Delayed working memory consolidation during the attentional blink. *Psychonomic Bulletin & Review*, 9, 739-743.

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

Wascher, E. (2005). The timing of stimulus localization and the Simon effect: An ERP study. ***Experimental Brain Research***, 163, 430-439.

Schankin, A., & Wascher, E. (2007). Electrophysiological correlates of stimulus processing in change blindness. ***Experimental Brain Research***, 183, 95-105.

Welford, A. T. (1952). The "psychological refractory period" and the timing of high speed performance—A review and a theory. ***British Journal of Psychology***, 43, 2-19.

Wolfe, J.M. (1994). Guided search 2.0: a revised model of visual search. ***Psychonomic Bulletin & Review***, 1, 202-238.

Wolfe, J.M., Cave, K.R., & Franzel, S.L. (1989) Gided search: an alternative to the feature integration model for visual search. ***Journal of Experimental Psychology: Human Perception and Performance***, 15, 419-433.

Woodman, G.F., & Luck, S.J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. ***Nature***, 400, 867-869.

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

Woodman, G. F., & Luck, S. J. (2003b). Dissociations among attention, perception, and awareness during object-substitution masking. ***Psychological Science***, 14, 605-611.