The temporal locus of the interaction between working memory consolidation and the attentional blink

ELKAN G. AKYÜREK, MARCIN LESZCZYŃSKI, AND ANNA SCHUBÖ

Department of Psychology, Ludwig Maximilian University, Munich, Germany

Abstract

An increase in concurrent working memory load has been shown to amplify the attentional blink. The present study investigated the temporal locus of this phenomenon, by using a dual rapid serial visual presentation paradigm that enabled the measurement of lateralized event-related potentials. The P3 component was shown to be affected by both working memory load and the lag between the target stimuli, consistent with current models of temporal attention and a functional explanation of the P3 in terms of memory consolidation. P3 amplitude was reduced for short target lags and high memory loads. The P2 component was affected by lag only, and not memory load. Importantly, the N2pc component was modulated also by both lag and memory load. The results showed that early attentional processing (as marked by the N2pc) was suppressed by increased involvement of working memory, a phenomenon not well predicted by many current theories of temporal attention.

Descriptors: Attentional blink, Working memory, Event-related potential, N2pc, P3

The study of temporal attention has enjoyed a surge of interest over the past two decades due to the discovery of the attentional blink phenomenon. The attentional blink (AB) is the marked difficulty of identifying the second of two briefly flashed, successive target stimuli if these follow each other within approximately 500 ms (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). A host of theories have attempted to explain the emergence of the attentional blink. The majority of these accounts focused on cognitive capacity limitations (e.g., Bowman & Wyble, 2007; Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Shapiro, Raymond, & Arnell, 1994), but more recently alternative models that are (relatively) capacity-free have also been proposed (Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Olivers & Meeter, 2008). Working memory is represented in both capacity-limited and capacity-agnostic models of the attentional blink, despite apparent discrepancies regarding its role. Without immediately going into more detail, it is important to stress that virtually all available models of either type hold that working memory operations are a relatively late process, in other words, taking place only after considerable attentional processing. As a consequence, any interference due to memory involvement during an attentional task is thus necessarily thought to have a late locus in the cognitive system. It is this

assumption that the current study sought to test. Before discussing the logic of this test in detail, it is appropriate to briefly characterize these existing models of the blink.

Starting with the class of capacity-limited models, these typically assume that the cognitive system is limited at a late stage of processing, responsible for memory consolidation and response selection, in which only one item can be processed at a time. Early stage processing is thought to proceed relatively freely, but representations of stimuli that cannot proceed to the next stage are prone to decay and interference. By contrast, models that attempt to avoid capacity limitations as a causal factor assume that it is not a lack of a given cognitive capacity that causes the blink, but rather that it is a consequence of the configuration of the attentional filter, which selects information for further processing. In the model of Di Lollo and colleagues, an executive control function called the "central processor" is required to maintain an appropriate attentional set, and when this processor is occupied by the processing of the first target stimulus, the system temporarily loses control and becomes vulnerable to exogenous, distractor-generated triggers, which causes the blink (Di Lollo et al., 2005). The model of Olivers and Meeter (2008) takes a slightly different approach, in which it is assumed that the attentional filter is too slow to "boost" the representation of a target stimulus upon its detection, and ends up boosting the next (irrelevant) item instead. This situation is then imperfectly corrected by the issue of an inhibitory "bounce" signal, which causes the blink by suppressing subsequent incoming stimuli for some time.

The discrepancy between these two types of models regarding the role of working memory in the emergence of the blink should be acknowledged at this point. Whereas the first, classic type of theory posits a major bottleneck at the consolidation of infor-

mation into working memory, the second type of theory assumes that, although working memory limits may indeed exist, they are normally not the main cause of the blink. In a direct test of this issue, the impact of loading working memory on the deployment of temporal attention was investigated by Akyürek, Hommel, and Jolicœur (2007). In this study, a classic attentional blink task was embedded within a memory-probe task. The memory task was contingent on the first target stimulus (T1), so that T1 served as the memory probe. Thus, participants were asked to detect T1 and to match its identity to a memory set presented at the beginning of each trial. The logic of this implementation was that this T1 contingency would lead observers to access their memory at the critical time; that is, they were *using* working memory during the attentional task, rather than having it as a relatively passive store. Increasing the (numerical) load on working memory load had a clear effect: A higher load impaired the identification of the second target stimulus (T2), and did so in particular at short T1-T2 lag, which resulted in a deeper attentional blink. The interaction between working memory and the attentional blink found here should be attributed to active use of memory, and not so much the mere maintenance of information, as previous studies indicated that the latter type of task does not interact with the blink (Akyürek & Hommel, 2005, 2006).

It would thus seem that theories attributing a critical role to working memory are vindicated. Yet, the behavioral evidence leaves some leeway in the theoretical interpretation. Even the nearly completely capacity-agnostic model of Olivers and Meeter (2008) assumes that processing delays could occur when working memory is filled, even if that does not normally cause the blink. As far as the study by Akyürek et al. (2007) is concerned, the interaction between AB magnitude and working memory load could be attributed to a temporary and perhaps exceptional overload of memory. Note that this assumption is only different from the one made by classic capacity-limited models in that the latter assume a working memory bottleneck underlies the AB even without additional memory load, whereas the former does not.

Either way, all of these current theories of the blink would place a working memory problem of any kind at a late phase of processing (but see also Wyble, Nieuwenstein, & Bowman, 2009), even though this has not been tested decisively. The available models would predict an initial phase of normal deployment of attention, with the memory consolidation problem arising only after feature identification. Early attentional processing is expected to be intact and fully completed. In classic models such as the one by Chun and Potter (1995), lack of memory (consolidation) resources would be a part of limited late stage ("Stage 2") processing. In the model of Olivers and Meeter (2008), it would similarly be a problem originating at or beyond the gating function that controls entry to memory, after stimulus identification (but not response mapping) has taken place.

To find the locus of interference in time, electrophysiology is a promising method, due to its ability to reveal the time course of processing in the brain with high precision. A number of studies on the attentional blink have employed electrophysiological measurements to date. The evidence they have brought forward is unfortunately mixed with regard to finding a single locus in time at which the blink occurs. Pioneering studies conducted by Luck, Vogel, and Shapiro (1996; Vogel, Luck, & Shapiro, 1998) showed that the P3 component of the event-related potential (ERP) is suppressed during the attentional blink, whereas the N400 component is not (see also Kranczioch, Debener, & Engel,

2003). Since the P3 is associated with consolidation in working memory, these results fit existing theory quite well (Donchin & Coles, 1988; Kok, 2001; Polich, 2007). The N400 component is associated with semantic processing, which presumably is a relatively advanced type of stimulus processing (Kutas & Hillyard, 1980). Its survival during the blink is somewhat paradoxical. However, a recent study by Giesbrecht, Sy, and Elliott (2007) has shown that the N400 does not survive if perceptual load is high (i.e., the target is hard to discern). They argued that the survival of the N400 in previous work was indicative of a postperceptual locus of selection, whereas high perceptual load such as used in their study necessitates selection at an earlier, perceptual level.

The evidence produced by these studies concerning earlier components is less clear. The P2 has been reported to decrease during the blink, as estimated by T1-T2 lag, by Vogel et al. (1998), but a slightly different approach based on the analysis of correct and incorrect trials by Kranczioch et al. (2003) has lead to the idea that blink-related processing starts only after the P2 time-window (beyond 300 ms post-T2). However, subsequent work has revealed earlier effects of the blink on the ERP, casting doubt on the hypothesis that the blink is exclusively the result of a late cognitive bottleneck. Sergent, Baillet, and Dehaene (2005) presented a thorough analysis of ERP components elicited in a dual target-mask paradigm, and found evidence for a divergence of the ERP between blink and no-blink trials at around 270 ms post-T2, around the time of the N2 component. Still earlier components were observed to be affected by the blink in a series of studies by Jolicœur, Dell'Acqua, and colleagues (Dell'Acqua, Sessa, Jolicœur, & Robitaille, 2006; Jolicœur, Sessa, Dell'Acqua, & Robitaille, 2006). In their studies, a dual stream rapid serial visual presentation (RSVP) paradigm was employed. This design carries the benefit that it allows for the measurement of lateralized attention, as indexed by the early N2pc component (Eimer, 1996; Kiss, van Velzen, & Eimer, 2008; Luck & Hillyard, 1994). In all of their experiments, the N2pc (peaking around 220 ms) was shown to be suppressed during the attentional blink. Since the N2pc component is thought to reflect the attentional processing of stimulus features at a particular location, a suppression of this component would seem to indicate a processing bottleneck at an earlier locus than what might be expected from a working memory depletion scenario. However, the electrophysiological evidence to date leaves the possibility open that the attentional blink is a multi-faceted phenomenon (a plausible claim made previously by, e.g., Kawahara, Enns, & Di Lollo, 2006). Namely, it might be that the late effects on the P3 component are indeed caused by the 'real' blink-related bottleneck, but that the earlier N2pc time range effects are due to other factors that perhaps contribute to the overall performance deficit, but that have their origin in stimulus-driven contingencies such as target or distractor salience. In a similar vein, for example, task and location switching have been shown to augment the blink, even though these are separable effects (Visser, Bischof, & Di Lollo, 1999).

Thus, in order to establish the locus of the memory bottleneck in time, it has to be studied in isolation of other factors that may contribute to the blink. The electrophysiological correlate of the interaction between working memory and the attentional blink offers just this possibility. Therefore, to test whether working memory has a late locus of interference with the attentional blink, as available theories would predict, the present study set out to investigate this issue by using the interaction between working memory and the blink as observed in the paradigm by Akyürek

et al. (2007) as a starting point for an electrophysiological investigation. In the present experiment, participants were asked to memorize a set of letters, and to match the identity of T1 in a subsequent RSVP stream to this memory set. The behavioral effect of both T1-T2 lag and that of memory set size (load) on T2 identification accuracy as well as the T2-locked ERP was examined.

Method

Participants

Twenty-two students (11 female, 11 male) at the Ludwig Maximilian University Munich participated in the experiment for course credit or monetary compensation. The electroencephalogram (EEG) data from the first participant were discarded because of a programming error that (only) affected the timing signals sent from the stimulus computer to the EEG acquisition computer. The behavioral data were retained. Participants were unaware of the purpose of the experiment and reported normal or corrected-to-normal vision. Mean age was 23.5 years (range 18–26 years).

Apparatus and Stimuli

Participants were individually seated in a comfortable chair in an acoustically and electrically shielded testing chamber that was dimly lit, at a distance of approximately 100 cm from the screen. The 20'' CRT screen was driven by a Core 2 Duo computer with a discrete graphics board, and refreshed at a frequency of 100 Hz with a resolution of 800 × 600 pixels in 16 bit color. The experiment was programmed in E-Prime 1.2. Responses were logged on a standard USB keyboard polling at 125 Hz. A light gray background was maintained throughout the experimental trials. A plus sign ("+") in 18 pt. Courier New font served as the fixation cross. The stimuli presented as the memory set were 36 pt. size red letters. The stimuli in the dual RSVP streams consisted mostly of 36 pt. size black letters. Amidst these black letters, T1 consisted of two identical red letters presented simultaneously in each stream, and T2 was a single red digit number. The letters for the memory set, and for each of the RSVP streams separately, were randomly chosen from all the letters of the alphabet, without replacement. The digit number for T2 was chosen from 2–9. The RSVP streams were aligned to the center of the screen and separated on the horizontal plane by 128 pixels.

Procedure and Design

The experiment started with 24 practice trials, which were excluded from all analyses, after which a total of 1200 experimental trials followed. There were two experimental variables (factors): Lag (0, 3, and 8) and memory Load (1 and 4). Lag 0 trials consisted of 'catch' trials, in which no T2 was shown and a normal distractor took its place. As explained below, catch trials were used to compute difference waves. T1 could appear at the 5th or 7th position in the stream, and it could either match or not match the memory set. T2 could appear in the left or the right stream. All of these trial types were randomly mixed and evenly distributed. Trials were self-paced and divided into 5 blocks of 240 trials each. Between blocks of trials, participants were encouraged to take a break. Participants initiated each trial by pressing "Enter." Each trial started with a blank screen of 100

ms, which was followed by the working memory set consisting of either one or four letters, which remained on screen for 1000 ms and was followed by an 800-ms blank screen. A fixation cross of 200 ms preceded the RSVP streams, and remained visible throughout the streams. The streams consisted of 20 stimuli each presented for 70 ms and followed by a 30-ms blank. After a delay of 100 ms, two successive response screens for T1 and T2 were presented for 1500 ms each, or until a response was given. For T1, participants were asked to judge whether T1 was part of the memory set or not. For T2, the task was to identify the digit number. At the end of the trial, a 200-ms blank pause allowed for the transmission of response signals to the EEG acquisition computer. Figure 1 shows a schematic representation of the main structure of the experimental trials.

Mean accuracy was analyzed using repeated measures analyses of variance (ANOVAs), with the factor T2 Lag (Lag 3 or Lag 8), and the factor Memory Load (1 or 4 items). Comparisons were made between short and long lags to estimate the effect of the blink. Note that this approach is conservative by design, as it includes contributions from both correct and incorrect trials at each lag.[1] In case of a significant test of sphericity, the degrees of freedom were adjusted using the Greenhouse-Geisser epsilon correction.

Electrophysiological Recording and Data Analysis

EEG was recorded with Ag-AgCl electrodes from 64 electrodes according to the extended International 10–20 System. The electrodes were referenced to Cz and re-referenced offline to the average of both mastoids. Horizontal electro-oculogram (EOG) was recorded from the outer canthi of the eyes and the vertical EOG from above and below the left eye. Electrode impedance was kept below 5 kΩ. The amplifier used a 125-Hz cut-off and a 0.1-Hz high-pass filter. EEG was recorded at a frequency of 500 Hz.

The data were filtered off-line with a 40-Hz low-pass filter at − 12 dB (48 dB/oct roll-off), and a 0.1-Hz high-pass at − 6 dB (24 dB/oct roll-off). EEG was averaged into 1000 ms segments, starting 200 ms prior to the onset of T2 and ending 800 ms afterwards. Ocular artifacts (blinks and eye movements) were corrected using the Gratton-Coles procedure (Gratton, Coles, & Donchin, 1983). For each electrode, trials with amplitudes exceeding ± 80 μV, voltage steps exceeding ± 50 μV between two sampling points, and trials with voltages lower than 0.10 μV for a 100-ms interval were excluded from analysis. A 200-ms pre-T1 interval (included in the artifact rejection procedure) was used for baseline correction. This interval was chosen rather than one

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[1]Although it is common to report conditional T2 performance (i.e., T2|T1), this approach was not taken in the present paradigm. The logic of the conditional approach is that only when T1 is reported correctly can one be sure that it has an effect on T2. Even if this is true, there is another method to ascertain the same: The difficulty of perceiving T2 depends critically on the temporal distance between T1 and T2. If T1 is not perceived, lag is meaningless. Thus, taking lag as an indicator of the blink is, in fact, a more conservative approach, as it includes trials on which T1 was perhaps perceived to some degree, but not sufficiently so for correct report, in which case the blink effect would be reduced. In the present study, there was, furthermore, a specific reason for not taking the conditional approach: The working memory task caused differences in T1 performance by design. When taking only T1-correct trials, low and high memory load trials would be composed of a systematically different number of trials, which might distort the averages. By taking the cautious approach of using all trials instead, this potential confound was avoided.
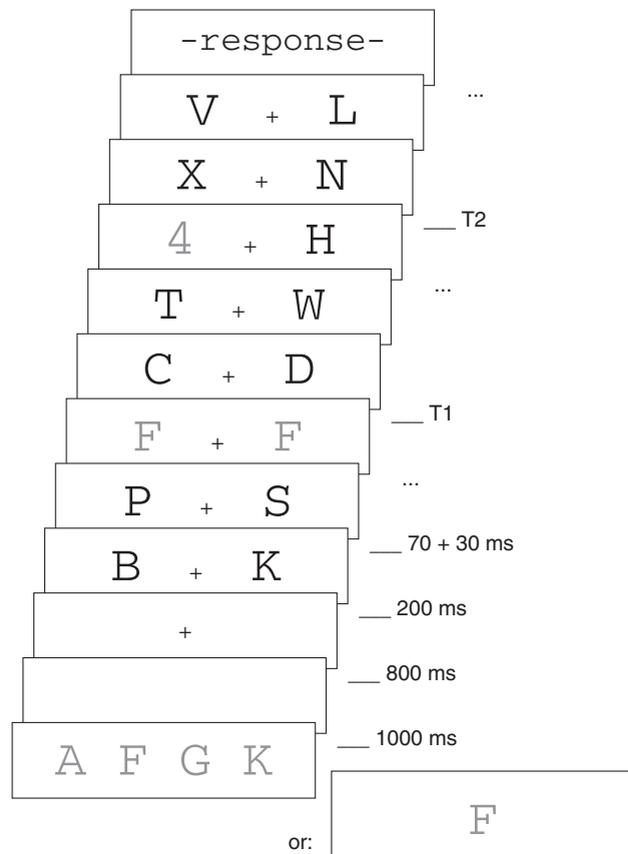
Figure 1. Schematic representation of the experimental trial structure. First, a memory set of 1 or 4 letters was shown. Second, after a delay and a fixation cross, two rapid serial visual presentation streams were presented (20 frames). Three dots (...) indicate the variable presence of several more intermediate RSVP frames. In the actual experiment, targets were red. Finally, two response screens queried the observers for their input.

preceding T2 to avoid Lag-dependent contamination of the baseline caused by the different temporal onsets of T1.

Separate ANOVAs were performed for mean amplitude values obtained in the time windows corresponding to the N2pc (150–260 ms after the onset of T2), the central-anterior P2 (170–260 ms), and the parietal P3 (320–500 ms). These time windows were chosen to be compatible with existing studies of these components, while fitting the presently observed peaks. The following electrodes were chosen for analysis: The PO7/PO8 pair for the N2pc, FCz for the P2, and Pz for the P3. The electrodes were chosen a priori to match those commonly used for these components. To calculate the N2pc, ipsilateral waveforms (i.e., recorded from the left hemisphere electrode site while T2 was in the left visual field, and the same for right hemisphere site and right visual field) were subtracted from contralateral waveforms (i.e., left hemisphere electrode site and right visual field, etc.). The resulting N2pc difference waveform reflects lateralized attention. The non-lateralized P2 and P3 components were calculated by means of another difference wave procedure. Since the dual RSVP paradigm elicits individual ERPs for each stimulus in the stream, the ERP of the target of interest is drowned in this activity. To get rid of the ERP components elicited by irrelevant stimuli, the ERP of the catch trials in which no T2 was shown was subtracted from the ERP of T2 trials (a very similar approach

was used by Vogel et al., 1998). The logic of this subtraction is that, because linear summation applies to EEG data, the ERPs to the irrelevant items cancel out against each other while the ERP to T2 is preserved. For reference, a set of raw ERP traces has been included as an Appendix.

Results and Discussion

Behavioral Results

Because of the high number of trials (1200) that was used to boost the signal-to-noise ratio for the ERP analyses, the behavioral analyses discerned even relatively small differences reliably. Figure 2 shows the performance on T1 (left panel) and T2 (right panel) as a function of lag.

T1 accuracy showed significant effects of both Lag, $F(1,21) = 10.88$, $MSE = .001$, $p < .005$, and Load, $F(1,1) = 164.34$, $MSE = .003$, $p < .001$. Performance was higher at Lag 8 (75.7%) than at Lag 3 (73.9%), and higher with low memory load (81.8%) than with high load (67.8%). Overall, the T1 task was relatively difficult for the observers. The lag effect on T1 reflected a degree of competition between targets, as has been found in RSVP studies before (Hommel & Akyürek, 2005; Potter, Staub, & O'Connor, 2002). The factors Lag and Load also interacted reliably, $F(1,21) = 5.47$, $MSE = .001$, $p < .05$. The interaction reflected a larger difference between high and low memory load at Lag 3 (15.2%) compared to Lag 8 (12.8%).

T2 identification accuracy was likewise affected by Lag, $F(1,21) = 29.83$, $MSE = .003$, $p < .001$, and Load, $F(1,21) = 18.80$, $MSE = .004$, $p < .001$. T2 identification performance was relatively high overall, probably due to the salience of T2 (red among black). Nonetheless, a blink was observed at Lag 3 where performance averaged 81.5%, compared to 88.3% at Lag 8. Mean performance was affected to a similar degree by Load; a high memory load resulted in 81.9% accuracy, and a low load in 87.9%. The interaction between Lag and Load was reliable as well, $F(1,21) = 19.67$, $MSE = .001$, $p < .001$. The blink was increased when memory load was high (76.6% vs. 87.1%, at Lag 3 and 8, respectively), compared to when it was low (86.3% vs. 89.5%). Comparison of the individual means showed that there was a significant blink even for the low memory load, $t(21) = 3.77$, $p < .001$. This pattern of performance replicated the results of Akyürek et al. (2007).

Electrophysiological Results

The N2pc showed significant main effects of both factors: Lag, $F(1,20) = 38.44$, $MSE = .518$, $p < .001$, and Load, $F(1,20) = 17.33$, $MSE = .302$, $p < .001$. A short lag between T1 and T2 reduced N2pc amplitude ($-.87\ \mu V$ at Lag 3 compared to $-1.84\ \mu V$ at Lag 8). Similarly, a high memory load reduced N2pc amplitude as well ($-1.10\ \mu V$ at Load 4 compared to $-1.60\ \mu V$ at Load 1). The interaction between Lag and Load was also significant, $F(1,20) = 4.67$, $MSE = .301$, $p < .05$. There was a stronger suppression of the N2pc by memory load at Lag 3.[2] There was a $-.76\ \mu V$ difference at Lag 3 compared to $-.24\ \mu V$ at Lag 8. To make sure the interaction effect was not driven by the outer end of the waveform (where visual inspection of the

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[2]An overall analysis including the two neighboring electrode pairs of PO3/PO4 and O1/O2 also showed a reliable interaction effect, $F(2,40) = 9.814$, $MSE = .067$, $p < .001$, indicating that, although the PO7/PO8 paid might have driven the effect, the pattern was the same on the other pairs.
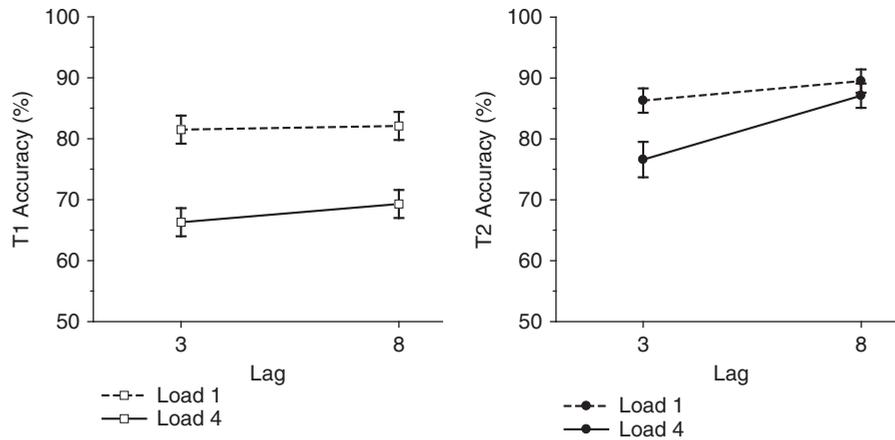
Figure 2. Behavioral performance on the experimental task. Memory match performance on T1 (left panel) and identification accuracy on T2 (right panel) is plotted separately for high and low memory loads (solid and dashed lines, respectively), as a function of T1-T2 lag. Error bars represent one standard error of the mean.

waveform might give rise to this suspicion), we conducted a second analysis in which we considered only the rising flank of the N2pc, by cutting the analysis time-window in half (i.e., 150–200 ms). This analysis revealed that the interaction between Lag and Load was reliable there also, $F(1,20) = 7.22$, $MSE = .397$, $p < .05$. The suppression of the N2pc by Load at Lag 3 was $-.92\,\mu V$, compared to $-.18\,\mu V$ at Lag 8. The N2pc results thus showed clear effects of working memory load and lag, indicating that relatively early attentional processing was affected by both. Figure 3 (upper left panel) shows lateralized differential amplitude as a function of time for the PO7/PO8 electrode pair.

For the P2 component, Lag had a reliable main effect, $F(1,20) = 13.53$, $MSE = 1.934$, $p < .001$. At Lag 3, P2 amplitude was close to zero (.11 μV), compared to the amplitude at Lag 8 (1.23 μV). Neither Load ($F < 1$) nor its interaction with Lag was reliable ($F < 2.5$). The results indicated that memory load did not have a detectable effect on P2 amplitude, even though the attentional blink (i.e., Lag) did. Figure 3 (upper right panel) shows ERP amplitude as a function of time for the FCz electrode.

The analysis of the P3 component showed significant effects of Lag, $F(1,20) = 20.06$, $MSE = 2.236$, $p < .001$, and of Load, $F(1,20) = 4.26$, $MSE = 3.184$, $p < .05$, as was expected. P3 amplitude averaged 2.87 μV at Lag 3, compared to 4.34 μV at Lag 8. A high memory load decreased the P3 amplitude (3.20 μV), compared to a low load (4.04 μV). The lag effect replicated established findings that the P3 is suppressed during the blink (e.g., Vogel et al., 1998). The effect of memory load was new, yet in the line of expectations given the functional attribution of the P3 to memory consolidation (e.g., Kok, 2001). The fact that T2 was rather salient in the presentation stream in the present paradigm likely prevented a complete suppression of the P3, as the component remained visible even when suppression was maximal. Figure 3 (lower panel) shows ERP amplitude as a function of time for the Pz electrode. There was a hint of residual RSVP noise in the waveforms, which may reflect a less-than-perfect outcome of the subtraction procedure. Since the number of catch trials amounted to only 1/3 of all trials, there may have been slight amplitude differences between these trials and the T2-present trials related to trial frequency. However, other than causing a small visual distortion, the residual activity did not influence the signal in a systematic way.

Current source density maps falling within the considered time windows for all four conditions are also shown in Figure 3. Since the underlying data for these maps consisted of difference waves, the maps should be considered with some caution. There was evidence for amplitude changes between lags as well as memory loads, which was consistent with the ERP analyses.

General Discussion

The present experiment intended to investigate the temporal locus of the interaction between working memory and the attentional blink. The results clearly showed that attentional processing is disrupted by working memory load at an early stage of processing. The primary evidence concerned the suppression of the N2pc component at high memory load, in addition to the suppression effect of short temporal lag. The lag effect has been demonstrated previously (Dell'Acqua et al., 2006; Jolicœur et al., 2006), but the memory load effect is the first evidence of an early effect of memory load on attentional processing in a dual-task situation, starting at 190 ms post-T2. In the present paradigm, the N2pc (like the P3) was attenuated rather than eliminated, which was presumably due to the salience of T2. Note that the salience of T2 would work against the hypothesis that memory processing should affect the N2pc, not for it. In any case, the results indicated that stimulus-driven salience is able to elicit an N2pc even when attention is taxed. The early effect of working memory load on attentional processing is not well predicted by the vast majority of available theories of temporal attention. Even though N2pc suppression during the blink has been observed previously (for T1-T2 lag), this effect could have been driven by a different, early component of the blink, such as backward masking (e.g., Kawahara et al., 2006), and thus does not necessarily connect a working memory bottleneck to the N2pc, while the present results do in two ways: First by the existence of a memory load main effect on the N2pc, and second by the interaction effect of memory load with lag, showing increased N2pc suppression at short lag. This connection is indeed notable, given the functional ties of the N2pc component to spatially specific processing of stimulus features (Kiss et al., 2008), rather than to memory operations. Indeed, it has been claimed that the N2pc is distinctly insensitive to memory pro-
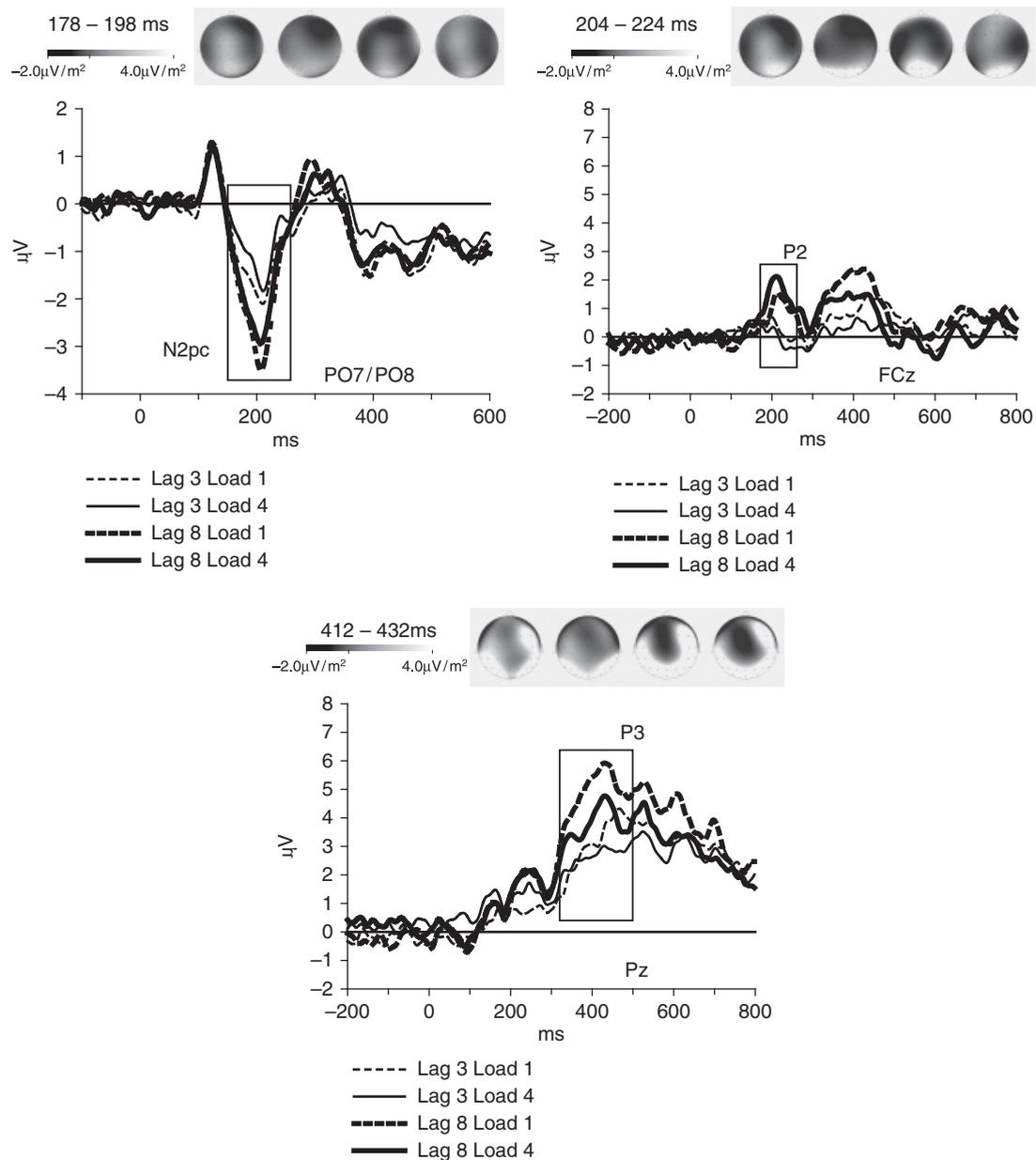
Figure 3. N2pc contra- minus ipsilateral difference waveforms (ΔμV) as a function of time in ms, recorded at the PO7/PO8 electrode pair (upper left). ERP amplitude in μV as a function of time in ms, derived from a difference wave procedure (see main text), recorded at FCz (upper right), and at Pz (lower panel). Time zero denotes T2 onset, and the box outline represents the analysis window. Topographical map insets were constructed using spherical spline interpolation and represent a 20-ms average centered on the observed waveform peaks of the difference waves (see main text). For each graph, from left to right, the maps represent Lag 3 & Load 1, Lag 3 & Load 4, Lag 8 & Load 1, and Lag 8 & Load 4.

cesses (Jolicœur, Brisson, & Robitaille, 2008). It is not claimed here that the N2pc reflects working memory consolidation, however. Recall that the experimental paradigm required access to working memory at the time of T1: The deployment of this process was then measured on the ERP of T2. Thus, the conclusion must be that working memory access impaired the deployment of spatially selective feature processing on subsequent stimuli—in other words, the results showed an effect of memory load on temporal attention.

The effects on the presently observed P2 component were somewhat of a puzzle. The amplitude of the P2 was affected by lag, but not by memory load. The functional significance of the P2 is unfortunately unclear, and the component is not always

observed in attentional blink tasks (Kranczioch et al., 2003; Sergent et al., 2005). Yet, the current results do suggest that the cognitive processes underlying the P2 component are qualitatively different from those associated with the P3 and N2pc. More research is obviously needed to investigate the role of the P2 in temporal attention.

Finally, replicating previous work, the present study showed the suppression of the P3 due to short temporal lag (Luck et al., 1996; Kranczioch et al., 2003; Vogel et al., 1998). The presence of the lag-induced P3 suppression confirmed the existence of a modulation at the stage of working memory consolidation. Such modulation is consistent with all available models of the blink, as the P3 can be thought of as the final result of attentional

processing. In other words, if interference is present at an earlier stage (e.g., at the attentional filter), this would affect downstream operations as well; filtered distractors do not need to be consolidated. The presently observed effect of memory load on the P3 component supported the behavioral results that pointed to an interaction between memory and attentional performance. Although an interaction effect, such as observed at the N2pc, was not apparent for the P3, this need not be surprising even if one were to expect a strong correlation between all ERP components and behavioral performance. As a consequence of attentional deployment, the P3 effect may be understood as another additive factor giving rise to the observed behavioral difficulty. Indeed, given the presence of earlier modulations of the ERP (i.e., of the N2pc), doubt is cast on the idea that increased working memory demands of T1 interfere exclusively with consolidation of T2.

Taken together, the present results demonstrated an early locus of interference between working memory and temporal attention. This finding is not well predicted by several models of the attentional blink (Bowman & Wyble, 2007; Chun & Potter, 1995; Di Lollo et al., 2005; Jolicœur & Dell'Acqua, 1998; Olivers & Meeter, 2008; Shapiro et al., 1994). Regardless of whether working memory consolidation plays the causal role in the development of the blink or not, none of these models would predict that

relatively early feature processing would be impaired by working memory load. In classic capacity-limited models, the interference suffered during the blink is located in late stage processing, in which consolidation, response selection, and full stimulus binding and identification take place. Feature processing is thought to be unimpaired (e.g., Chun & Potter, 1995). A more recent model by Wyble and colleagues (2009) does offer a way to incorporate the present findings. In this model, a direct link exists between working memory encoding and attention, such that early attentional deployment could be stalled by working memory load. Thus, this newly developed model shows an adaptation that other models would need to make as well. In capacity-agnostic models, working memory interference would be just a limit on the number of items that can be stored in memory (Olivers & Meeter, 2008). Running into such a limit is not normally supposed to give rise to the blink, and it would not be expected to interfere with feature processing. The present results show that there are links between late processing stages involved in accessing working memory and earlier ones in dual-tasks, and during the attentional blink. Theories of temporal attention should thus accommodate the idea that spatially specific attention not only freezes as a consequence of the blink, but also as a consequence of working memory operations.

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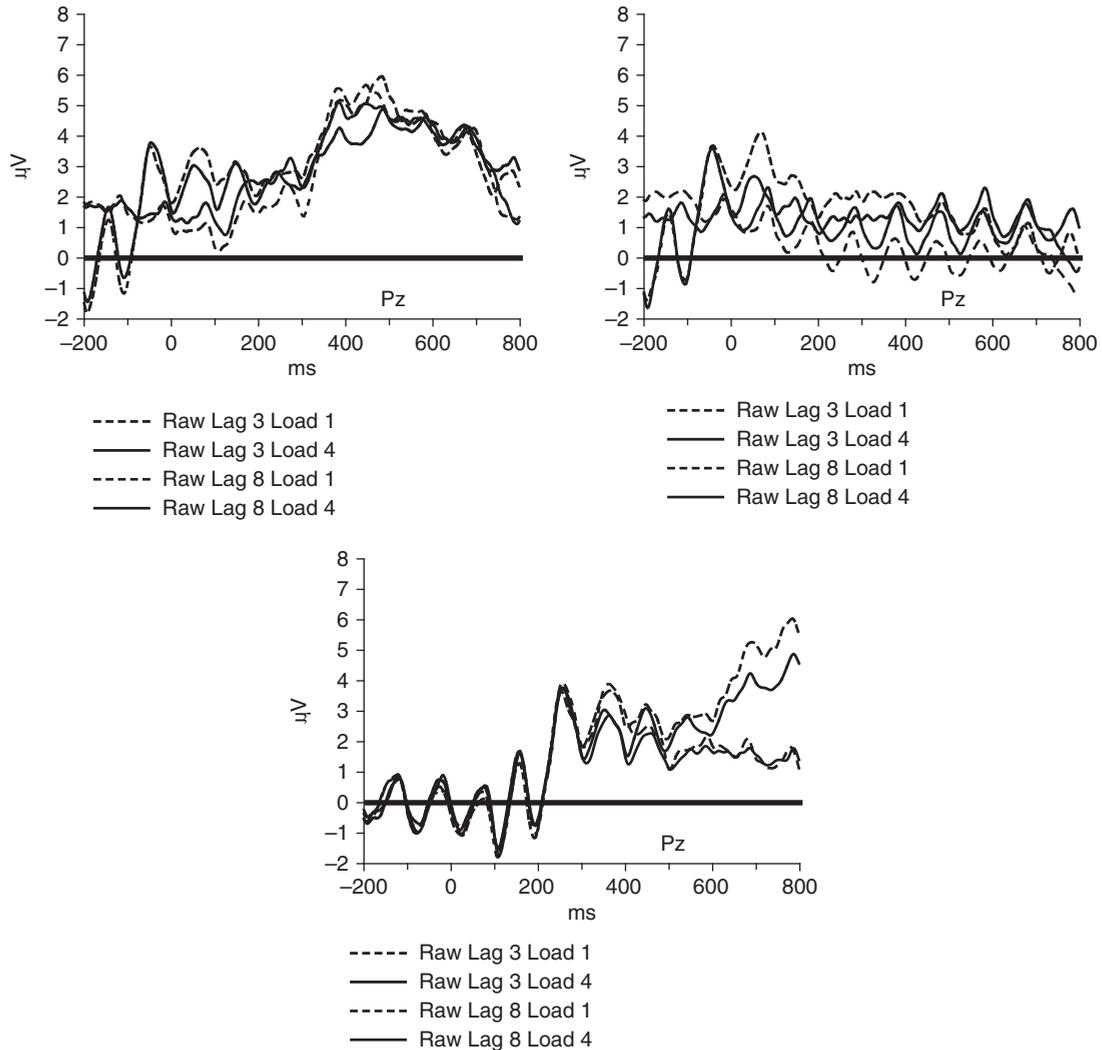
APPENDIX

Figure A1

Figure A1. Raw ERP amplitude relative to T2 onset in μV as a function of time in ms recorded at the Pz electrode (upper left panel). Raw ERP amplitude used for difference wave subtraction (see main text) in μV as a function of time in ms recorded at Pz (upper right panel). Raw ERP amplitude relative to T1 onset in μV as a function of time in ms recorded at Pz (lower panel). Identical to the processing of all the presently reported ERP data, the baseline used here was the 200 ms interval before T1 onset.