

Electrophysiological evidence of visual encoding deficits in a cross-modal attentional blink paradigm

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Abstract

Two experiments are reported in which two target stimuli, T1 and T2, were presented at variable stimulus onset asynchronies (SOAs). In Experiment 1, T1 and T2 were visual stimuli embedded in a rapid serial visual presentation (RSVP) stream of distractors. Participants were asked to report T1 and T2 at the end of the stream. In Experiment 2, T1 was an auditory stimulus, and T2 a visual stimulus embedded in an RSVP stream. Participants made a speeded discriminative response to T1, and reported T2 at the end of the stream. An attentional blink (AB) effect was observed in both experiments: T2 report suffered at short SOA compared to long SOA. During the AB, the amplitude of the P300 component of the event-related potential (ERP) locked to T2 onset was sensibly reduced in both experiments. Behavioral and ERP results were very similar across the two experiments. Implications for models of the AB effect are discussed.

Descriptors: Attentional blink, P300, Visual memory, Cognitive limitation

Two different paradigms have been used extensively to study attentional limitations affecting the processing of two sequentially presented targets: The attentional blink (AB) paradigm and the psychological refractory period (PRP) paradigm. In both paradigms, performance on the second target is strongly dependent on the time interval between the onset of the first target and the onset of the second target (i.e., stimulus onset asynchrony or SOA), whereas performance on the first target is affected much less by the SOA manipulation. In the AB paradigm, the two targets (usually designated as T1 and T2) are often embedded in a stream of distractor stimuli presented using the rapid serial visual presentation (RSVP; e.g., Raymond, Shapiro, & Arnell, 1992) method. Generally, the accuracy of report of T2 is impaired when the SOA between the two targets is shorter than 500–600 ms and T1 must also be processed. This decrement in report accuracy is the AB effect. In the PRP paradigm, the stimuli are usually presented in isolation, and speeded responses are made to each stimulus. The PRP effect is a progressive increase in response time to the second stimulus as the SOA between the two stimuli is reduced (see Pashler, 1994, for a review).

Despite the difference in method used to investigate the AB effect and the PRP effect, recent empirical work and theorizing about these two attentional deficits have illuminated some interesting similarities concerning the functional causes of these attentional deficits (Crebolder, Jolicoeur, & McIlwaine, 2002; Jolicoeur, Dell'Acqua, Crebolder, 2001; Luck & Vogel, 2001; Ruthruff & Pashler, 2001). Although early work on the AB effect suggested a perceptual locus (e.g., Raymond et al., 1992), later work has implicated a late, postperceptual locus of this effect (e.g., Jolicoeur & Dell'Acqua, 2000; Luck, Vogel, & Shapiro, 1996; Vogel, Luck, & Shapiro, 1998). There is also considerable evidence for a late locus of interference in the PRP paradigm (Pashler & Johnston, 1989; see Pashler, 1994, for a review). Thus, performance deficits in both paradigms reflect postperceptual capacity limitations.

The results of Vogel et al. (1998) suggesting a late locus of AB interference are particularly interesting. The second target in one of their experiments (Experiment 2, p. 1662) was a word, whereas the first target was a string of repeated digits. These targets were presented in an RSVP stream consisting of strings of random letters. The RSVP stream was preceded by a context word (exposed for 1,000 ms). The target word could either be semantically congruent or semantically incongruent with the context word. The subjects were instructed to report the digit, and indicate whether the context word and the target word following the digit were semantically congruent words or not. The event-related potentials (ERPs) time-locked to the target word onset were recorded. A strong AB effect was observed: When the target word followed the digit at an intermediate SOA (252 ms), the semantic judgment accuracy was substantially

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lower than at the other SOAs (84 and 588 ms). In contrast, the magnitude of the N400 response to semantically incongruent words had the same normal amplitude at all SOAs. The N400 response suggests that T2 was identified and processed to the level of meaning. Furthermore, the fact that the N400 response did not vary with SOA suggests that the meaning of the target words was activated at all three SOAs (thus, independently on the AB). In a different experiment, Vogel et al. found a reduced P300 response to an infrequent T2 letter stimulus presented during the AB (Experiment 4, p. 1666). Although different interpretations have been proposed for the P300 response (e.g., Donchin, 1981; Verleger, 1988), there is a general consensus that P300 represents electrophysiological evidence for the updating of information in working memory (WM; Donchin & Coles, 1988; Johnson, 1986). Findings of a suppressed P300 wave time-locked to T2 during the AB have thus been taken as evidence that the AB reflects a failure to encode T2 into visual WM (VWM; Vogel et al., 1998). The fact that the SOA manipulation in the AB paradigm does not affect the magnitude of the N400 response suggests that the AB does not prevent the retrieval of semantic information associated with T2. Jointly, these two results suggest that targets that cannot be reported because of the AB have, nonetheless, been fully identified (intact N400), but have not been encoded into VWM (suppressed P300).

The results obtained by Vogel et al. (1998) provide strong support for models that postulate that the AB phenomenon is an encoding deficit, and is caused by limitations at a stage of processing involved in consolidating the transient perceptual representation of T2 into a durable VWM representation (Chun & Potter, 1995; Jolicoeur, 1998; Jolicoeur & Dell'Acqua, 1998, 1999; Wong, 2002). When consolidation is engaged for T1, consolidation of a fleeting and temporarily unstable T2 must wait, increasing the probability that the perceptual representation of T2 decays, or is masked by trailing stimuli (Brehaut, Enns, & Di Lollo, 1999). According to the attentional dwell model (Ward, Duncan, & Shapiro, 1996), identification and/or detection of serially presented visual targets draws on a common pool of attentional resources. In this framework, the AB effect reflects the reduced availability of attentional resources for the consolidation of T2 in VWM when a portion of these resources is allocated to the consolidation of T1 in visual VWM. A model that is not included in the aforementioned subset is the proposal advanced by (Shapiro, Raymond, and Arnell 1994; see also Maki, Frigen, & Paulson, 1997; Raymond, Shapiro, & Arnell, 1995), according to which the AB effect arises after T1, T2, and distractors immediately following T1 and T2 in the RSVP stream have already reached the status of VWM representations. The attentional blink is explained, in this optic, in terms of interference affecting T2 at or just before a retrieval stage, due to the presence in VWM of concurrently active, competing items.

Other evidence suggests that encoding information into VWM is subject to processing capacity limitations. Jolicoeur (1999), for instance, combined the requirement of making a speeded response to an auditory T1 with the delayed report of a visual T2. T1 was a pure tone presented at two frequencies. T2 was always a target letter embedded in an RSVP stream of distractors. Subjects made a speeded choice response to T1 based on pitch, and reported T2 without speed pressure at the end of each trial. The logic of this paradigm rested on the idea of using a first task known to cause a PRP effect in the PRP paradigm, and merging it with a task normally employed in AB studies in order to test whether the presentation of T1 and T2 in cross-modal

conditions would bring about an AB effect. Indeed, large and reliable AB effects were consistently found in this and similar paradigms (Jolicoeur, 1999; see also Dell'Acqua & Jolicoeur, 2000; Dell'Acqua, Turatto, & Jolicoeur, 2001; Jolicoeur, Dell'Acqua, & Crebolder, 2000). The similarity between the impairments described by Jolicoeur and those found in typical AB experiments suggest a possible functional similarity in the underlying causes of the two effects. Jolicoeur argued that both response selection and short-term consolidation are mental operations carried out by central mechanisms, such that both are subject to mutual interference when engaged concurrently for the execution of temporally overlapping, independent tasks (see also Arnell & Jolicoeur, 1999).

Our present goal was to test the hypothesis that the performance deficit described by Jolicoeur (1999), like the deficit observed in typical AB experiments, can be characterized in terms of a failure to update VWM when T2 is temporally contiguous to T1. This would provide evidence that using a speeded task on an auditory T1, which is typical in most PRP designs, generates the same consequences on T2 processing as those hypothesized to be subtended in the AB effect observed in RSVP contexts, in which all stimuli are presented visually and targets are associated with delayed responses. We did this by focusing on the P300 component elicited by a masked T2 embedded in an RSVP stream of distractors. In Experiment 1, we set out to replicate the results obtained by Vogel et al. (1998), and so T1 and T2 were both visual stimuli embedded in an RSVP stream that had to be reported without speed pressure at the end of the trial. In contrast, in Experiment 2, T1 was an auditory stimulus associated with a speeded choice task. In both experiments, we measured the accuracy of report of T2 and the ERP locked to the onset of T2. Given previous results (e.g., Jolicoeur, 1999), we expected to find an AB effect in both experiments, and we expected that the AB effect produced in Experiment 1 would be reflected in a large reduction of the P300 component of the ERP locked to the onset of T2 (Vogel et al., 1998). The new empirical question was whether a similar effect would also be found in Experiment 2, in which the performance deficit in Task 2 was generated by a different, cross-modal task performed in response to T1. Suppression of the P300 wave time-locked to T2 following the cross-modal, speeded Task 1 in Experiment 2 would provide further converging evidence for a similarity between the underlying cause of the visually elicited AB (in the "standard paradigm") and the cause of the cross-modal effect reported by Jolicoeur (1999).

EXPERIMENT 1

In Experiment 1, we used the same experimental settings and methodology as those used by Vogel et al. (1998) in their Experiment 4. Stimuli were displayed using the RSVP method. Each RSVP stream contained two target stimuli that had to be identified and reported with no speed pressure at the end of the RSVP stream presentation. The first target stimulus (T1) was a digit, and the second target stimulus (T2) was the letter *E* on 25% of the trials, or a different letter (chosen randomly among all letters except *E*) on the remaining 75% of the trials. On half of the blocks of trials, subjects had to report the digit in T1, and report whether an *E* was present in the stream of stimuli following T1. On the other half of the blocks of trials, the digit in T1 could be ignored, and only T2 required an overt response.

The use of task-defined stimulus categories for T2 differing in frequency (25% *E* vs. 75% non-*E* trials) is tied to a specific difficulty that is encountered with ERP quantification under RSVP conditions. A target item in the RSVP stream generates an electrical perturbation that lasts several hundred milliseconds following its onset, and overlaps considerably with analogous electrical perturbations evoked by the items preceding and following the target item in the same stream. Isolating a P300 component elicited by the target item in this context with the use of standard techniques is problematic. To solve this problem, Vogel et al. adopted a variant of the irrelevant-probe technique developed in ERP studies on spatial attention (e.g., Luck & Hillyard, 1995). The logic behind the use of this technique hinges on two demonstrated facts. The first fact is that voltage fields summate linearly. The second fact is that the P300 amplitude is probability sensitive, with larger P300 components elicited by stimuli falling in the less frequent task-defined stimulus category (Donchin, 1981). Jointly, these two facts provide the necessary support to the following assumption. On the hypothesis that the ERP elicited on *E* trials is the sum of an enlarged P300 response and an electrical response modulated by the other items in the RSVP stream, whereas the ERP elicited on non-*E* trials only reflects the response to the other items in the stream, a pure P300 response to the stimulus *E* may be isolated by subtracting the ERP generated on non-*E* trials from the ERP response generated on *E* trials. This technique was used to generate the electrophysiological results of Experiment 1 and Experiment 2.

Method

Seventeen observers volunteered to participate, all with normal or corrected-to-normal vision. The stimuli were black (0.4 cd/msq) uppercase letters (A–Z) and white (25 cd/msq) digits (1–9) presented on a gray (11 cd/msq) background. The stimuli were presented at the center of the monitor of a computer, at a rate of 10 items per second (no interstimulus interval). Each character subtended 1.0 degree of visual angle in height and in width. The viewing distance was approximately 60 cm. Each trial began with the presentation of a fixation point at the center of the screen that disappeared upon trial initiation. After 600 ms, the RSVP of characters began. There were 6 to 9 randomly selected letters prior to a digit (T1), and 10 to 12 letters following T1. T2 was either the first, third, or ninth letter following T1, corresponding to a T1-T2 SOA of either 100, 300, or 900 ms, respectively. T2 was the letter *E* on 25% of the trials. On the remaining 75% of the trials, T2 was one letter selected at random from the set of available letters excluding *E*. In five blocks of 60 trials each, observers pressed one of two keys (i.e., the keys 1 and 2 of the numeric keypad of the keyboard) at the end of the RSVP to indicate whether the T1 digit was odd or even, and they pressed a third key (i.e., the key *E* of the keyboard) to indicate whether one of the letters following T1 was the letter *E*. In another five blocks, observers ignored T1 and only indicated whether one of the letters following T1 was the letter *E*. In both types of trials, when T2 was not the letter *E*, observers moved on to the beginning of the next trial by pressing the space bar. The order of block types (single-task vs. dual-task) was random.

Electroencephalographic (EEG) activity was recorded from tin electrodes located at sites Fz, Cz, Pz (10/20 System; Jasper, 1958), referenced to the mastoids. Vertical eye movements (EOG) were bipolarly recorded from one electrode above and

one electrode below the left eye. The EEG and the EOG were amplified with a bandpass filter of 0.05–40 Hz, at a sampling rate of 250 Hz, and with a gain of 2500 (accuracy 0.034 $\mu\text{V}/\text{LSB}$, range ± 1.1 mV). Impedance at each electrode site was maintained below 5 K Ω . A number of steps were taken to reduce and quantify EEG data. First, a regression procedure to remove ocular artifacts from the EEG recordings was applied to the continuous bioelectrical data. Epochs associated with the stimulus in the T2 position, which extended temporally from 200 ms prestimulus to 1,000 ms poststimulus, were extracted from the continuous data, and the bioelectrical signal at each recording site within each epoch was baseline corrected using the mean activity recorded during the 200-ms prestimulus period. At any electrode location, epochs in which EEG activity exceeded ± 100 μV were eliminated. ERP waveforms included only epochs time-locked to T2 onset that were associated with a correct response to T1. Trials containing ocular artifacts, movement artifacts, or amplifier saturations were excluded from the averaged ERP waveforms (11%). Separate grand average waveforms for each condition and for each stimulus category were finally generated, and difference waves were constructed by subtracting the ERP waveforms elicited by the frequent T2 category (non-*E* letter) from the ERP waveforms elicited by the infrequent T2 stimulus category (*E*). The P300 component amplitude values were estimated based on these difference waves as the mean amplitude 300–700 ms poststimulus,¹ relative to the 200-ms prestimulus baseline.

Behavioral data (mean percent accurate responses to T1 and mean hit rate for responding *E* when *E* was presented in T2) and electrophysiological data (i.e., mean P300 amplitude values in the subtracted ERP waveforms) were submitted to analysis of variance (ANOVA), in which the task on T1 (single-task vs. dual-task), and SOA (100 ms vs. 300 ms vs. 900 ms) were treated as within-subject factors. Recording site (Cz vs. Fz vs. Pz) was included as an additional within-subject factor in the analysis performed on the electrophysiological data.

Results

Behavior

Mean T2 report accuracy is shown in Figure 1 (upper panel) as a function of the task on T1 (either report T1, labeled Dual-Task in the figure, or ignore T1, labeled Single-Task in the figure), and as a function of SOA. T2 performance was lower in the dual-task condition than in the single-task condition at the two shorter SOAs, but was nearly equivalent across single-task and dual-task conditions at the longest SOA. Significant effects of both T1 task, $F(1,16) = 133.3$, $p < .01$, SOA, $F(2,32) = 4.0$, $p < .04$, and their interaction, $F(2,32) = 12.6$, $p < .01$, were found. In the dual-task condition, T2 performance at the two shorter SOAs did not differ

¹In this study, we report and discuss electrophysiological results obtained by considering a P300 component amplitude calculated on the basis of a time window of 300–700 ms. This time window differs slightly from the time window considered by Vogel et al. (1998) in an analogous experimental context (i.e., 400–800 ms). Although the present time window seems to capture with more precision the overall P300 amplitude extension (from the latency of the earliest notable deviation from baseline of the ERP function to its return to baseline after reaching the positive peak), we also performed parallel analyses for Experiment 1 and Experiment 2 on P300 amplitudes based on a time window of 400–800 ms, finding no difference between the two sets of statistical analyses.

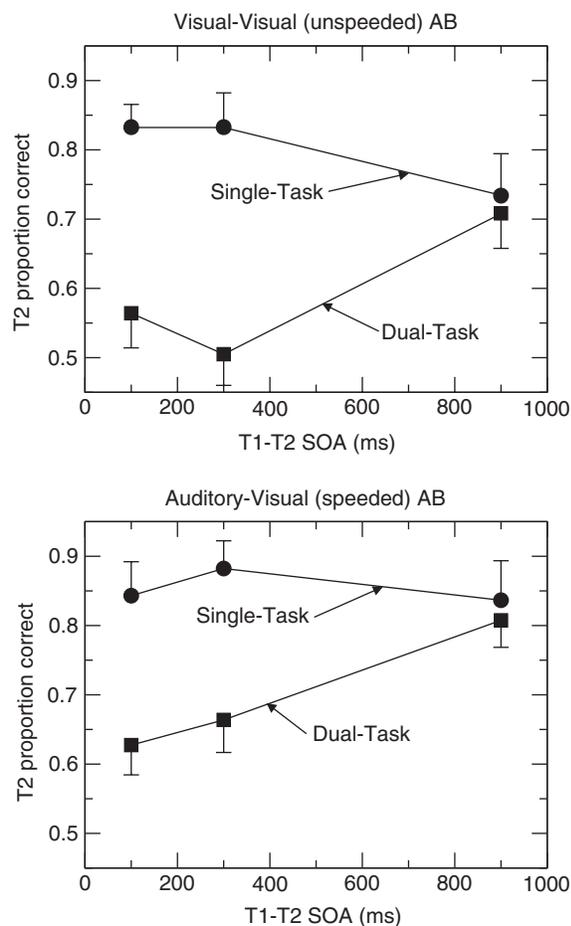


Figure 1. Behavioral results in Experiment 1 (upper panel) and in Experiment 2 (lower panel).

significantly, $F(1,16) = 2.0$, $p > .2$. Mean T1 report accuracy was 0.96, with no effect of SOA, $F < 1$.

ERP

Subtracted grand-average waveforms locked to T2 onset are shown in Figure 2 as a function of the task on T1, as a function of SOA, and as a function of recording site. An additional perspective on the results from one of the recorded channel is provided by Figure 3, where unsubtracted waves generated from signals recorded over Pz are graphically reported as a function of SOA and task on T1. In both figures, the P300 is evident in all panels as a positive (downward) deflection of each ERP waveform peaking around 500 ms. The analyses performed on the subtracted waves amplitudes revealed that the amplitude of the P300 component increased progressively from Fz to Pz recording sites, $F(2,32) = 10.1$, $p < .01$. Whereas ample and comparable P300 components were elicited by T2 at all SOAs in the single-task condition (left panels), a progressive P300 component suppression was apparent at all sites as SOA decreased in the dual-task condition (right panels). This gave rise to significant effects of T1 task, $F(1,16) = 7.0$, $p < .02$, and a T1 Task \times SOA interaction, $F(2,32) = 6.7$, $p < .01$.² These results were constant across recording sites; there was no interaction

between site, T1 task, and SOA, $F < 1$. When the data from the longest SOA condition were not taken into consideration in the context of a separate analysis of the dual-task condition, no difference was found in P300 amplitude between the shortest (100 ms) and intermediate (300 ms) SOAs, $F(1,16) = 2.2$, $p > .18$.

Discussion

The results of Experiment 1 share a number of important similarities with those obtained by Vogel et al. 1998, (Experiment 4). On the behavioral side, a robust AB effect was found. When participants had to identify a T1 digit and detect a prespecified T2 letter, performance in the task on T2 worsened as the T1-T2 SOA was decreased. When instead T1 could be ignored, and the only task participants had to carry out on a trial was T2 detection, performance in the task on T2 showed a general improvement and, more importantly, was not affected by the systematic manipulation of the T1-T2 SOA. The behavioral results were complemented by electrophysiological results indicating that the P300 component time-locked to T2 onset was preserved at all T1-T2 SOAs when T1 could be ignored, whereas a progressive suppression of the P300 component was observed as the T1-T2 SOA was decreased when the T1 digit had to be processed. The parallel results between the P300 component amplitude and accuracy in the task on T2 converge nicely with the results reported by Vogel et al. (1998).

The present results and those obtained by Vogel et al. (1998) are different from each other in one critical aspect. As can be noted in the behavioral pattern of results reported in Figure 1 and in the electrophysiological results reported in Figure 2 and in Figure 3 participants' performance in the detection task on T2 at the shortest SOA (100 ms) was as impaired as the performance at the intermediate SOA (300 ms). Namely, the present results do not show evidence of the lag-1 sparing effect that was clearly manifest in Vogel et al.'s behavioral and electrophysiological results. Lag-1 sparing is defined as the attenuation (in some cases, elimination) of the AB effect when the SOA between T1 and T2 is equal to or shorter than 100 ms (e.g., Chun & Potter, 1995; Potter, Chun, Banks, & Muckenhoupt, 1998). In fact, the results of Vogel et al.'s Experiment 4 revealed that performance in T2 detection at the shortest SOA (83 ms) was as good as the performance in the task on T2 at the longest SOA (581 ms), with the AB affecting T2 performance at the intermediate SOA (249 ms) only. Consistent with the behavioral data, the P300 component amplitude was suppressed at the intermediate SOA, and preserved at the shortest and longest SOAs. Visser, Bischof, and Di Lollo (1999) reviewed the AB literature to determine the conditions under which lag-1 sparing is found. According to the results of their meta-analysis, lag-1 sparing is most likely observed when the perceptual and spatial sets defining T1 and T2 are particularly homogeneous, and when the criteria defining the responses to T1 and T2 are identical. In this perspective, the lag-1 sparing effect found by Vogel et al. in most of their experiments is somewhat surprising. The paradigm used by Vogel et al. in Experiment 4, like the paradigm used in the present Experiment 1, represents a case in which all conditions highlighted by Visser et al. are concomitantly violated. T1 was a white digit and T2 was a black letter. These two stimuli differ not only perceptually, but also semantically. Furthermore, the task on T1 required identification of the digit for the final odd/even categorization (i.e., a two-alternative forced choice task) of

²A Huynh-Feldt correction was used for the estimation of F statistics associated with more than one degree of freedom in the numerator.

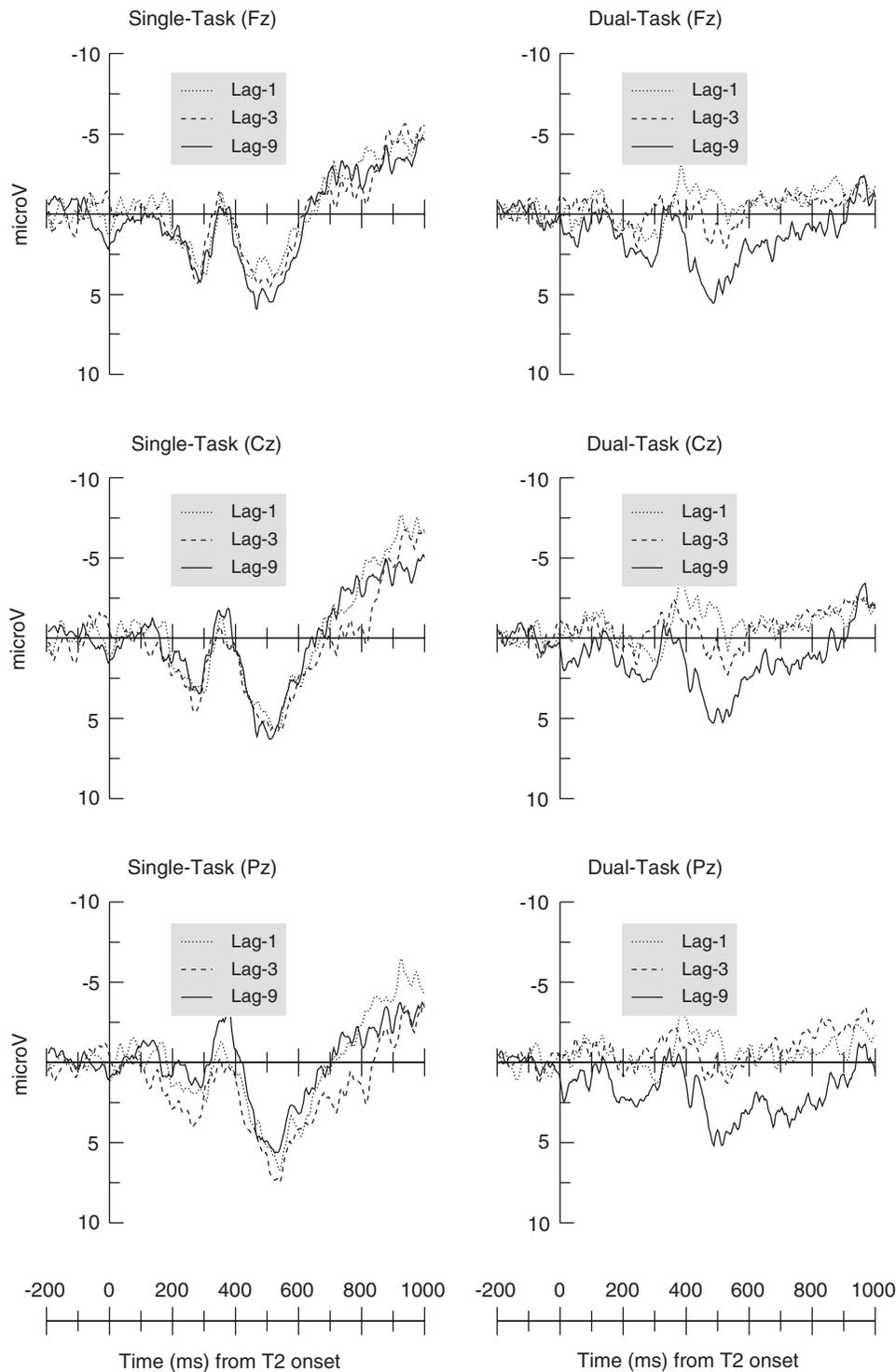


Figure 2. Electrophysiological results in Experiment 1. Grand-average difference waveforms (T2 E – T2 random letter) recorded under single-task conditions (left panels) and dual-task conditions (right panels).

the digit identity, whereas the task on T2 required detection of a prespecified target letter (i.e., a go/no-go task).

A partial reconciliation between the present results and those of Vogel et al. (1998) may be attempted by considering some notable exceptions to the regularities concerning the lag-1 sparing effect outlined by Visser et al. (1999). Potter, Staub, and O'Connor (2002), for instance, have recently observed lag-1 sparing effects under conditions in which T1 and T2 were words

presented in different spatial locations (i.e., above and below a central fixation point) and the SOA between T1 and T2 was decreased to reach durations shorter than 100 ms. These results were unexpected from the point of view of Visser et al. Potter et al.'s (2002) results are suggestive of the critical role of time, as opposed to the similarity in perceptual and/or response sets between T1 and T2, in generating lag-1 sparing effects in AB designs. Lag-1 sparing, in Potter's view, would more likely be

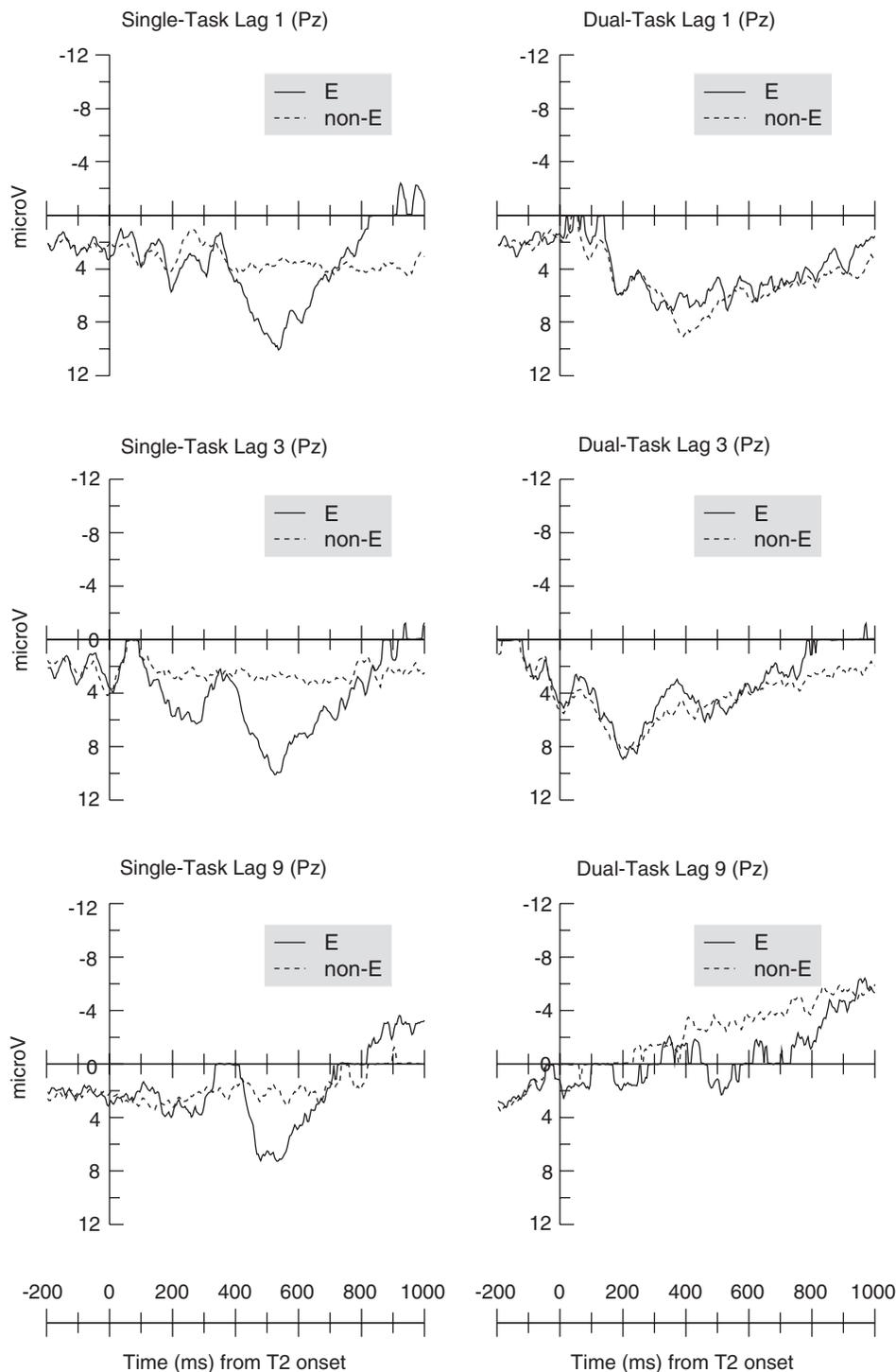


Figure 3. Electrophysiological results in Experiment 1. Grand-average waveforms recorded at Pz site plotted separately for the frequent T2 condition (T2 non-*E*) and the infrequent T2 condition (T2 *E*).

observed when the SOA between T1 and T2 is shorter than 100 ms (and independently on the number of items intervening between T1 and T2). In this alternative perspective, it might be that the different SOAs used in the present context than those used in Vogel et al.'s study make it more likely to observe a lag-1 sparing effect in Vogel's et al. study than in the present study. As a matter of fact, the shortest SOA used by Vogel et al. (83 ms) falls in the range of durations in which Potter et al. found a lag-1

sparing effect, which was not consistent with the rules suggested by Visser's et al. meta-analysis.

EXPERIMENT 2

Experiment 1 provided a nice conceptual replication of the attenuation of the P300 response to T2 during the AB reported

by Vogel et al. (1998). These results establish the adequacy of our methods and provide comparison results for those of Experiment 2. In Experiment 2 we used the same stimulus presentation and task for T2 as had been used in Experiment 1, but we replaced the visual T1 that was used in Experiment 1 by a simple auditory stimulus requiring a speeded choice response. Jolicoeur (1999) found that this first task caused a significant AB effect in report accuracy for T2. We expected to replicate this behavioral finding. The new empirical question was whether we would also observe an attenuated P300 response to T2 at short T1-T2 SOAs relative to that observed at a long SOA.

Method

Seventeen observers volunteered to participate, all with normal hearing and normal or corrected-to-normal vision. None had participated in Experiment 1. The visual stimuli were uppercase letters, and the sequence of visual events was the same as in Experiment 1. The auditory stimuli were 50 ms pure tones, with a frequency of 550, 900, or 1400 Hz. The tone (T1) was presented in the position occupied by the digit in Experiment 1. The digit was replaced with a randomly selected letter other than *E*. T2 was either the first, third, or ninth letter following T1, corresponding to a T1-T2 SOA of 100, 300, or 900 ms, respectively. T2 was an *E* on 25% of the trials, and a different letter otherwise. In five blocks of 60 trials each, an immediate and speeded response was required to T1. Observers rested the index, middle, and ring fingers of the right hand on the 1, 2, and 3 keys of the numeric keypad of the computer keyboard, and pressed one of these buttons to indicate that the pitch was low, medium, or high, respectively. Another key was pressed (not speeded) at the end of the trial to indicate whether one of the letters in the RSVP stream was an *E*. In another five blocks, observers ignored T1 and only indicated whether one of the letters in the RSVP stream was an *E*. In both types of trials, when T2 was not an *E*, observers moved on to the beginning of the next trial by pressing the space bar. The order of block types (Respond-to-T1 vs. single-task) was randomized for each observer. EEG and EOG recordings were made as in Experiment 1.

Results

Behavior

Data associated with artifacts, incorrect responses to T1, or reaction times to T1 (RT1s) longer than 2 s (10%) were excluded from further analysis. Mean hit rate for T2 trials in which *E* was presented can be seen in Figure 1 (lower panel) as a function of the task on T1 (either respond-to-T1, labeled Dual-Task in the figure, or ignore T1, labeled Single-Task in the figure), and as a function of SOA. T2 performance was relatively stable across SOAs in the single-task condition, whereas a progressive decrease in T2 report accuracy was observed in the Respond-to-T1 condition as SOA decreased. This produced a large difference between the single-task versus the dual-task conditions at short SOAs, but nearly identical performance at the longest SOA. This pattern of results was reflected in the ANOVA by significant effects of both T1 task, $F(1,16) = 15.0, p < .01$, and by a T1 Task \times SOA interaction, $F(2,32) = 5.5, p < .01$. In the dual-task condition, T2 performance at the two shorter SOAs did not differ significantly, $F < 1$. Mean T1 report accuracy was 0.90, and mean RT1 was 601 ms, with no effects of SOA, $F < 1$, in all cases.

ERP

Subtracted grand-averaged waveforms locked to T2 onset are shown in Figure 4 as a function of the task on T1, as a function of SOA, and as a function of recording site. Unsubtracted waves generated from signals recorded over Pz are reported in Figure 5. The analyses performed on subtracted waves amplitudes revealed that the amplitude of the P300 component increased progressively from Fz to Pz recording sites, $F(2,32) = 12.5, p < .01$. The P300 components elicited by T2 were comparable in amplitude across SOAs in the single-task condition (left panels). The P300 component was progressively reduced as SOA decreased in the Respond-to-T1 condition (right panels). A significant T1 Task \times SOA interaction, $F(2,32) = 7.3, p < .01$, was found. No interaction was found between T1 task, SOA, and site, $F(4,64) = 1.4, p > .22$. When the data from the longest SOA condition were not taken into consideration in a separate analysis of the dual-task condition, no difference was found in P300 amplitude between the shortest (100 ms) and intermediate (300 ms) SOAs, $F(1,16) = 2.0, p > .17$.

Discussion

The behavioral results in Experiment 1 and Experiment 2 were very similar. We found large AB effects affecting the report of a visual T2 both when T1 was also a visual stimulus to be reported at the end of the trial, and when T1 was an auditory stimulus associated with an immediate choice reaction time (CRT) task. These results were much as expected based on several previous demonstrations that an AB effect can be generated by T1 tasks that produce PRP effects manifest as SOA-dependent RT lengthening in speeded T2 tasks (e.g., Jolicoeur, 1998, 1999). The results suggest strongly that the short-term consolidation of T2 (Jolicoeur & Dell'Acqua, 1998) is susceptible to interference from both concurrent consolidation of a stimulus in the same modality or from concurrent processing required for a speeded choice response to a stimulus in a different sensory modality.

The crucial findings are the electrophysiological results obtained in the present study. The electrophysiological consequences on a key indicator of T2 performance were also very similar in Experiment 1 and Experiment 2. More specifically, the P300 component of the ERP time-locked to T2 onset was attenuated during the AB critical interval in both experiments, suggesting that interference on T2 processing must have occurred at or before the mechanisms that are responsible for the generation of the P300 response. There is a general consensus that the P300 response represents electrophysiological evidence for the successful update of information in WM (Donchin & Coles, 1988). More appropriately for the present context of investigation, we reviewed evidence that suggests that the P300 is an indicator of consolidation of new information in a VWM (Vogel, Luck, & Shapiro, 1998). The reduction in P300 amplitude found in both the present experiments suggests that the typical AB, in which both targets are masked visual stimuli, and the AB caused by a cross-modal speeded choice task are both reflections of interference at an encoding stage involved in T2 processing. In other words, the present results provide electrophysiological evidence that T2 does not reach the status of a representation in VWM, both in a classical unimodal RSVP paradigm and in the cross-modal paradigm originally designed by Jolicoeur (1999), in which the visual T1 associated with a

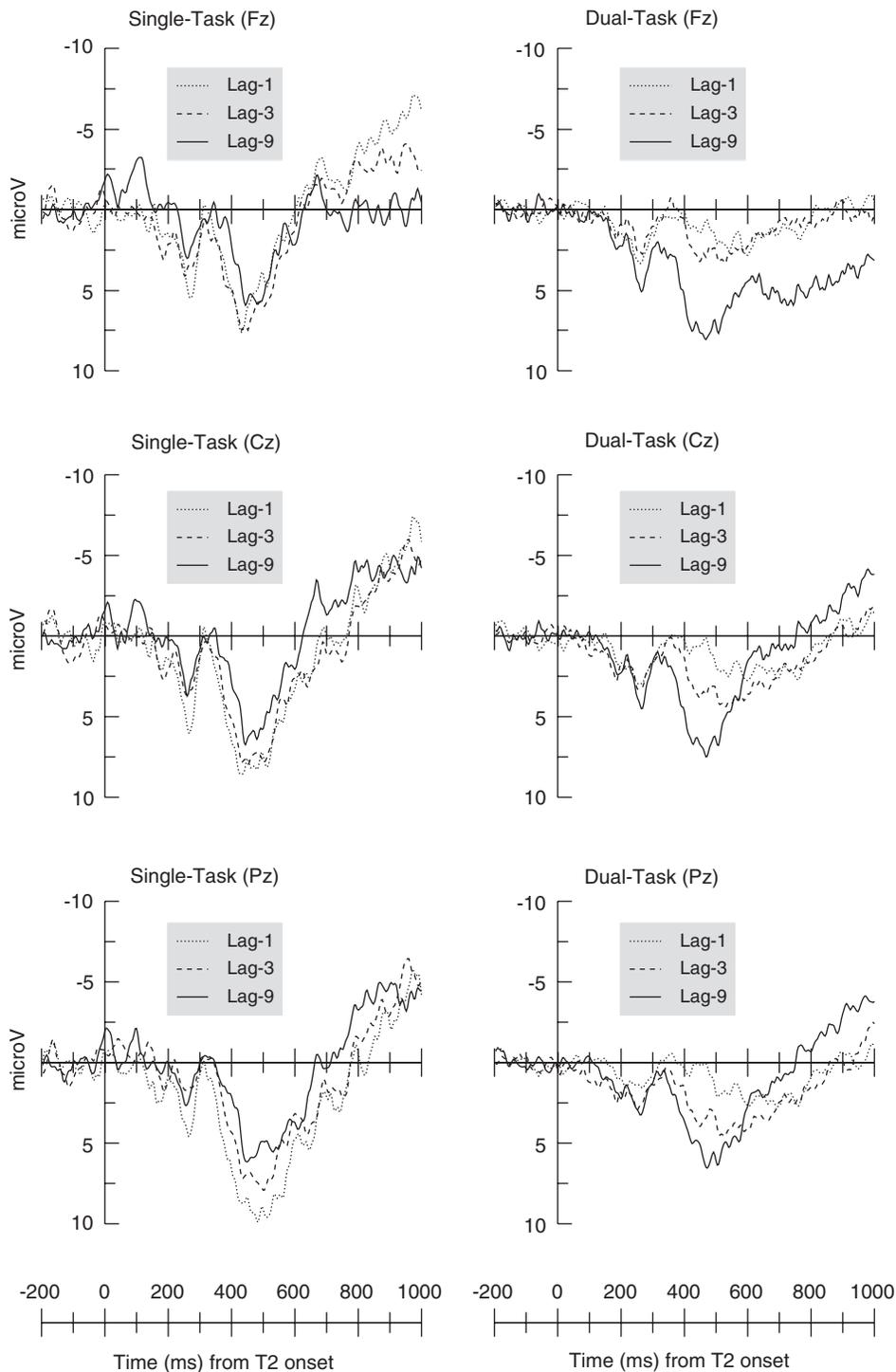


Figure 4. Electrophysiological results in Experiment 2. Grand-average difference waveforms ($T2 E - T2$ random letter) recorded under single-task conditions (left panels) and dual-task conditions (right panels).

delayed report task was replaced with a pure tone requiring a speeded choice response.

General Discussion

A number of models of the AB effect are based on the hypothesis that the AB effect occurs when transferring information out of VWM (e.g., Shapiro, Raymond, & Arnell, 1994; see also Isaak,

Shapiro, & Martin, 1999; Maki, Couture, Frigen, & Lien, 1997, for analogous proposals). These models assume that the AB effect is due to retrieval competition between T1 and T2 (and distractors immediately following T1 and T2 in the RSVP stream of stimuli) when T1 and T2 have already been encoded as WM representations. Much of the support for these models has come from results indicating that incorrect responses to T2 at short lags tend to be nonrandom, that is, subjects tend to report distractors

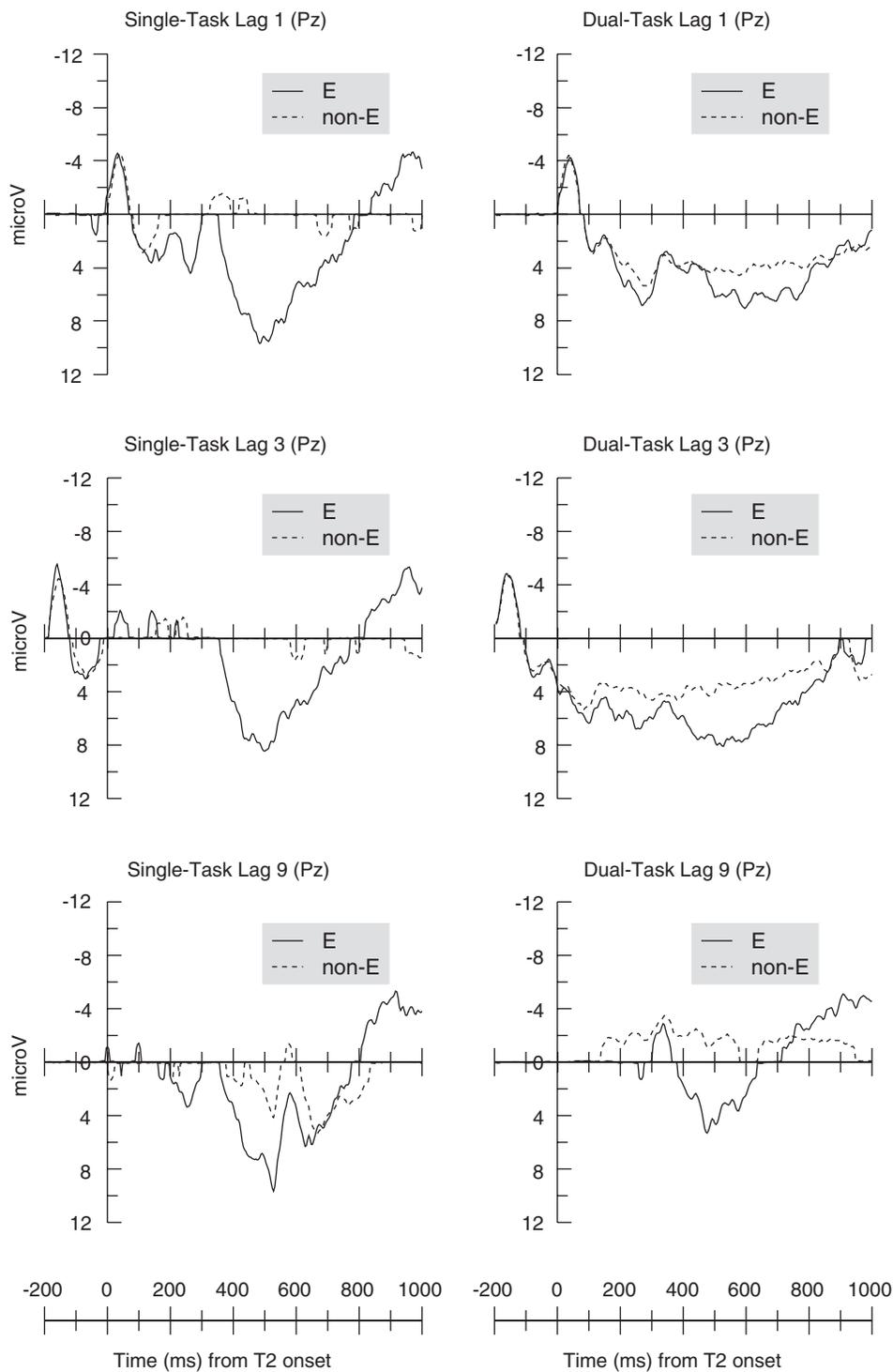


Figure 5. Electrophysiological results in Experiment 2. Grand-average waveforms recorded at Pz site plotted separately for the frequent T2 condition (T2 non-*E*) and the infrequent T2 condition (T2 *E*).

immediately following T2. This approach cannot account for the present results in a number of ways. One way is related to the physical format of the stimuli used in Experiment 2. In Experiment 2, T1 was a pure tone and the task on T1 was a speeded pitch-discrimination task. Consequently, there is no reason to expect that any representation of T1 would enter VWM, and hence there should be no competing representations in VWM that would interfere with the report of a visually

presented T2. Furthermore, these models cannot easily account for the electrophysiological aspects of the present findings. As is clear, had T2 existed as VWM representation some time after its presentation in the present experiments, the P300 amplitude would not have been affected by the SOA manipulation. On the other hand, nonrandom errors are not in contrast with the alternative class of models that we have considered in the present context, that is, models of the AB as an encoding deficit. Models

in this class share the assumption that a short-lived conceptual representation is generated for all items embedded in a RSVP stream following a high-capacity first stage of processing. Nonrandom errors in this perspective are explained as reflections of the competition between concurrently active items at this first stage when attempting to select T2 for entry in VWM via a consolidation stage of processing (Chun & Potter, 1995; see also Jiang & Chun, 2001).

In previous work, we argued that part of the processing required to generate a representation for T2 that can provide the basis for an overt report (Duncan, 1980) is subject to central capacity limitations (Jolicoeur & Dell'Acqua, 1998, 1999). The present results provide additional support for the view that the AB deficits observed by Jolicoeur (1999), using mixed PRP/AB designs, belong to the same class of deficits as observed in AB experiments using uni-modal RSVP paradigms. In the same vein, we argue that the most parsimonious explanation of the present findings is that consolidation and response selection are both operations that require central resources that cannot be shared easily across tasks (Arnell & Jolicoeur, 1999). When such operations are required for the execution of temporally overlapping tasks, mutual postponement or some other form of mutual interference of one or both operations results in slower and/or more error-prone performance, particularly for the second target stimulus. The results of Experiment 1 and Experiment 2 are, in this framework, analogous manifestations of interference on the short-term consolidation (Jolicoeur & Dell'Acqua, 1998) of T2 mediated, respectively, by concurrent consolidation of T1 and by concurrent response selection for the speeded task on T1. Both of these manifestations were clearly reflected in the lower T2 report accuracy and attenuated P300 responses in the ERP time-locked to T2 onset.

Distinct aspects of the present study are congruent with results of recent ERP investigations in the attentional domain. Vogel and Luck (in press) have found evidence of onset latency delays of the P300 time-locked to T2 at short T1-T2 lags in a paradigm in which T2 was always the last item in each RSVP stream (i.e., T2 was not masked). Under these conditions, there was no AB, presumably because T2 was not masked (Giesbrecht & Di Lollo, 1998). When T2 is not masked, some representation of T2 is assumed to persist and remain available for later consolidation despite a period of waiting while the short-term consolidation of T1 takes place. However, if the consolidation of T2 is delayed while the consolidation of T1 takes place, one would expect to see a delayed, but otherwise normal (i.e., normal amplitude) P300 response to T2. The delay of the P300 response should only occur at short T1-T2 lags, when contention for the consolidation bottleneck would be more likely to occur. At longer lags, the consolidation of T1 would already be complete by the time T2 was presented, and no delay should be observed. This is essentially what was observed by Vogel and Luck. The present findings suggest an important generalization of this specific proposal to experimental designs in which T1 task and modality are changed to be congruent with what is generally implemented in PRP designs, that is, a speeded response to an auditory stimulus. The absence of the P300 component at short T1-T2 lags in the present Experiment 1 and Experiment 2 is conversely explained by the fact that T2 was masked, such that T2 was no longer available for consolidation because trailing stimuli presented during the period of postponement degraded or replaced the representation of T2. The similarity of the results across Experiments 1 and 2 suggest that the consolidation of T2

can be delayed at short T1-T2 lags either by the ongoing consolidation of T1 (Experiment 1) or by response selection for T1 (Experiment 2).

Arnell, Helion, Hurdelbrink, and Pasiaka (in press) used a paradigm in which a masked visual T1 associated with delayed report was followed by an auditory T2 requiring a speeded two-alternative forced choice response, much in the same way as Jolicoeur and Dell'Acqua (1998) did in several published experiments (see also Dell'Acqua & Jolicoeur, 2000; Jolicoeur & Dell'Acqua, 1999). As expected based on these previous demonstrations, Arnell et al. observed a progressive response time (RT) lengthening to T2 as the T1-T2 SOA was decreased. Interestingly, Arnell et al. also focused on the P300 component time-locked to T2 onset, and found an SOA-dependent P300 onset latency delay of an extent equivalent to the RT delay. On the assumption that consolidation and response selection are both operations requiring central resources, and on the assumption that either operation is postponed under overlapping task conditions in mixed PRP/AB designs, this pattern of results converges with the results obtained in the present study. Specifically, given that central mechanisms were likely to be first allocated to T1 consolidation in the design used by Arnell et al., central mechanisms were unavailable to carry out response selection for T2 under short T1-T2 SOA conditions. Central processing for the task on T2 was therefore temporarily postponed, and this was reflected in postponement of the onset of the P300 component time-locked to T2 onset. Furthermore, as expected based on the present proposal, the overall extent of the SOA-dependent interference on T2 processing (142 ms; i.e., RT to T2 at the longest SOA minus RT to T2 at the shortest SOA) was equivalent to the overall delay in P300 onset observed from the longest SOA to the shortest SOA (122 ms).

It is still unclear what a P300 component reflects in the context of speeded tasks carried out on unmasked stimuli. Some evidence suggests that P300 cannot be mapped onto processing occurring at a response selection stage. Specifically, using a classical PRP design and a subtraction method similar to the method used in the present context, Luck (1998) focused on the latency of the P300 time-locked to T2 onset. Luck found that the P300 latency was only modestly delayed as SOA was shortened, despite a substantial PRP effect on T2 RT. This suggests that the functional locus of the RT delay in PRP designs (likely, response selection; see Pashler, 1994) is after the stage of processing whose activity is reflected in the P300 component. This would obviously be in conflict with our proposal of a central processing limitation as a common (and possibly unique) cause for the entire family of AB deficits, PRP deficits, and mixed PRP/AB deficits. Although we believe that more work is required to exactly disentangle this apparent conflict, we are prone to notice some details in Luck's work that might help avoid perfunctory conclusions based on this study. In our view, it may be critical to note that, although the delay in P300 onset amounted to only 25% of the RT delay manifest in the PRP effect, Luck's analyses of the electrophysiological results revealed a statistically significant and substantial reduction of the P300 amplitude at the shortest SOA compared to the P300 of normal amplitude found at the longest SOA, suggesting a possible trade-off of these two electrophysiological quantifications of the P300 wave. Whether instead both of these aspects (onset delay and partial suppression of the P300 component) are to be taken into account when extrapolating the logical implications of Luck's elegant study is presently a matter of investigation in our labs.

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