Visual, auditory, and cross-modality dual-task costs: Electrophysiological evidence for an amodal bottleneck on working memory consolidation

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When two masked, attended targets (T1 and T2) are presented within approximately half a second of each other, report of T2 is poor, compared with when the targets are presented farther apart in time—a phenomenon known as the attentional blink (AB; Raymond, Shapiro, & Arnell, 1992). Some researchers have suggested that an amodal bottleneck on working memory consolidation underlies the AB (see, e.g., Arnell & Jolicœur, 1999). In the present work, T1 was masked, whereas T2 was unmasked. The modality of T1 (visual or auditory) and the modality of T2 (visual or auditory) were factorially manipulated across four experiments. For all modality combinations, T2's P3 event-related brain potential component was found to be delayed when T2 was presented soon after T1 (lag 3), compared with when T1 and T2 were presented farther apart (lag 8). Results suggest that the working memory consolidation bottleneck is amodal in nature, and provide evidence that visual, auditory, and cross-modality ABs all result from a bottleneck on consolidation operations.

When two masked targets both require attention, and are presented within half a second of each other, report of the second target (T2) is poor (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). In contrast, T2 report is unimpaired when T2 is presented more than half a second after the first target (T1), or when T1 does not require attention (Raymond et al., 1992). This temporary reduction in the accuracy of T2 report has been called the attentional blink (AB; Raymond et al., 1992). Almost all theoretical models of the AB suggest that T2 performance suffers while limited capacity attentional resources are occupied with the processing of T1 (Shapiro, Arnell, & Raymond, 1997). Some of these models postulate a bottleneck on conscious stimulus identification and/or consolidation. For example, in their two-stage model, Chun and Potter (1995) propose that T2 is processed through the first stage, in which a high level visual representation is created and meaning information is extracted. When T1 and T2 are separated by a large amount of time, T2 processing can then proceed to stage 2, in which it is consciously identified and encoded in working memory for report. Stage 2 processing is expensive in terms of time and resources. This means that when T2 follows soon after T1, and T1 is still undergoing stage 2 processing, T2 must wait to gain access to stage 2. If T2 is trailed by a mask, its temporary representation will be overwritten by the mask, stage 2 processing will fail, and subsequent report accuracy will be reduced, resulting in an AB. Jolicœur (1998, 1999) and Jolicœur and Dell'Acqua (1998, 1999) have similarly proposed a bottleneck on stimulus consolidation, whereby consolidation of T2 into working memory cannot proceed until consolidation of T1 has been completed. These authors further suggest that the processing resources needed for stimulus consolidation in working memory are the same as those required for response-selection operations.

Both behavioral and electrophysiological studies have provided clear evidence supporting these models' assumption of a postperceptual locus of the AB. For example, the AB is reduced if T2 is the participant's own name (Shapiro, Caldwell, & Sorensen, 1997) or a taboo word (Anderson, 2005). Also, a blinked T2 can semantically prime a subsequent target (Shapiro, Driver, Ward, & Sorensen, 1997). Luck, Vogel, and Shapiro (1996) showed that the N400 event-related brain potential (ERP), which is sensitive to semantic match/mismatch, is fully intact during the AB, indicating semantic activation of T2. There is also evidence to support the assumption that it is T2 stimulus consolidation that is impaired or delayed during the AB. For example, Vogel, Luck, and Shapiro (1998) and Vogel and Luck (2002) found that the difference wave for the P3 ERP component was dramatically attenuated during the AB. The P3 (or P300) size differs for rare and frequent task-defined events. The fact that the P3 is modulated by the task-defined frequency of events means that the P3

must occur after a stimulus has been identified and categorized as one of these (frequent) or one of those (rare). Subtracting the ERP activation on frequent trials from the ERP activation on infrequent trials yields a P3 difference wave ($P3_{dw}$). The latency and amplitude of this $P3_{dw}$ can then be used to estimate the timing and any attenuation of identification and categorization operations for the given target. Although the P3 is sensitive to task-defined stimulus probability, the P3 is not sensitive to response-selection operations (see, e.g., Magliero, Bashore, Coles, & Donchin, 1984), placing the P3 in a fairly narrow window after identification/categorization but before response-selection processes. Indeed, one popular notion is that the P3 reflects consolidation into working memory (Donchin, 1981; Donchin & Coles, 1988; Luck, 1998; Vogel & Luck, 2002). Thus, reduced $P3_{dw}$ amplitude during the AB suggests reduced working memory consolidation for T2 during the AB.

According to bottleneck models of the AB, the AB could be eliminated if T2 were unmasked, because the perceptual representation of T2 could outlast the bottleneck and be used to consolidate T2. Indeed, Giesbrecht and Di Lollo (1998) observed a robust AB when a T2 was trailed by a single item in a rapid serial visual presentation (RSVP) stream, but no AB for T2 when the trailing item was removed, even when T2 accuracy was kept below ceiling with the use of a superimposed integration mask. Vogel and Luck (2002) examined the $P3_{dw}$ time-locked to an unmasked T2 and found that the $P3_{dw}$ was intact, but occurred later when targets were presented closely in time, compared with when they were presented farther apart in time. Their results suggest that T2 consolidation occurred later at shorter target separations because of T2's wait at the consolidation bottleneck. Therefore, when a masked T2 is presented during the AB interval, T2 accuracy is reduced, as is the size of the $P3_{dw}$. However, when an unmasked T2 is presented during the AB interval, T2 accuracy is not reduced, $P3_{dw}$ size is not reduced, but the $P3_{dw}$ is pushed back in time.

AB Outside the Visual Modality

Although there is mounting evidence that ABs with visual targets result, at least in part, from a bottleneck in working memory consolidation, there is controversy about whether or not the AB-like patterns that are observed when one or more targets are presented outside the visual modality reflect this same working memory consolidation bottleneck. AB effects have been observed when both targets are presented auditorily (Arnell & Jenkins, 2004; Arnell & Jolicœur, 1999; Arnell & Larson, 2002; Duncan, Martens, & Ward, 1997; Mondor, 1998; Shulman & Hsieh, 1995; Soto-Faraco & Spence, 2002). Hillstrom, Shapiro, and Spence (2002) have also reported an AB when both targets were tactile in nature. Cross-modality AB effects have also been observed when one target is visual and the other is auditory (Arnell & Jenkins, 2004; Arnell & Jolicœur, 1999; Arnell & Larson, 2002; Shulman & Hsieh, 1995) and when one target is visual and the other is tactile (Soto-Faraco et al., 2002). However,

cross-modality and auditory AB effects are often smaller and more difficult to obtain than purely visual AB effects. For example, Potter, Chun, Banks, and Muckenhoupt (1998) found no AB when one or more targets were auditory unless the target tasks required a switch in task set from T1 to T2. Duncan et al. (1997) and Soto-Faraco and Spence (2002) reported no cross-modality ABs for auditory and visual target pairings. Arnell and Jenkins (2004) observed auditory and cross-modal AB effects when T2 was from the same alphanumeric class as the distractors (letter T2 among letter distractors), but not when T2 was from a different alphanumeric class than the distractors (digit T2 among letter distractors).

Auditory and cross-modality AB effects may be smaller and more difficult to observe than visual AB effects because they do not arise from the same processing limitation as ABs with visual targets (Potter et al., 1998). However, it is also possible that the same bottleneck on working memory consolidation underlies visual, auditory, and cross-modality AB effects, but that AB effects that include auditory target(s) are simply more difficult to produce, given the greater difficulty in masking these targets. Iconic memory is very complete, but very brief. As shown by Giesbrecht and Di Lollo (1998) and by Duncan, Ward, and Shapiro (1994), a single pattern mask trailing T2 is sufficient to replace T2 in iconic memory. Thus, a single mask trailing each target can ensure that T1 and T2 cannot be processed offline at the end of a trial. In contrast, echoic memory can last several seconds, with events unfolding over time (Cowan, 1984). Therefore, a single auditory mask may not replace a previous target in echoic memory—instead, both mask and target can be replayed. (For example, using echoic memory, you can "play back" in your head a whole sentence you heard two seconds before, not just the last word of the sentence.) Thus, to the extent that an auditory target can be played back at the end of a trial, T1 and T2 accuracy could remain high even during short separations, and even in the presence of a working memory bottleneck. Unless one looked for evidence of *when* T2 was consolidated, one would not know whether T2 survived a consolidation bottleneck by delaying T2 consolidation or never encountered a bottleneck at all. One can measure the timing of a participant's buttonpress response to T2. When T1 is a typical AB target (masked and requiring an unspeeded response at the end of the trial), and T2 is an unmasked target requiring a speeded response, results have consistently shown that T2 reaction times (RTs) increase as T1 and T2 are presented more closely in time (Arnell & Duncan, 2002; Arnell, Helion, Hurdelbrink, & Pasieka, 2004; Jolicœur & Dell'Acqua, 1998, 1999). Many such results have been observed with cross-modality T1 and T2 pairs, and therefore could provide evidence for a consolidation bottleneck with cross-modality targets. However, the requirement of a speeded response for T2 makes it difficult to know whether T2 RTs were delayed at short target separations because of consolidation delays or response-selection delays. Similarly, Dell'Acqua, Jolicœur, Pesciarelli, Job, and Palomba (2003) presented participants with an auditory T1 requiring a speeded re-

sponse, and a masked visual T2 requiring an unspeeded response. They observed reductions in T2 accuracy and T2 $P3_{dw}$ amplitude at short T1–T2 stimulus onset asynchronies (SOAs), when compared with long SOAs, suggesting that identification and consolidation operations may be impaired even with cross-modal AB targets. However, the use of a speeded response for T1 complicates this interpretation, given that any T2 deficits could also result from the response-selection requirements of a speeded T1 response. Therefore, in the present study, an unspeeded response will be required to both targets (a masked T1 and an unmasked T2), but the $P3_{dw}$ will be used to track the timing of working memory consolidation for T2.

The present study is modeled on a condition from Vogel and Luck (2002), who presented a masked visual T1 and an unmasked visual T2, each requiring an unspeeded response. They observed that the $P3_{dw}$ to T2 was delayed at short target separations, when compared with long target separations, providing evidence for a bottleneck on working memory consolidation with visual targets. In the present study, the results of Vogel and Luck were replicated (Experiment 1) and then extended to explore the case of two auditory targets (Experiment 2) and cross-modality visual and auditory targets (Experiments 3 and 4). If the bottleneck on working memory consolidation is amodal in nature, then the T2-locked P3 ERP component should be delayed at short T1–T2 lags, when compared with longer lags, in all four experiments. However, if the working memory consolidation bottleneck is modality specific in nature, P3 delays at short lags should be observed in Experiments 1 and 2, but not in Experiments 3 and 4. If the bottleneck is restricted to visual processing, then the P3 delay at short lags should be observed only in Experiment 1.

EXPERIMENT 1

Experiment 1 was a replication of the unmasked T2 condition of Vogel and Luck (2002). Both T1 and T2 were presented visually and required unspeeded responses, as in the typical AB paradigm. T1 was masked by trailing RSVP items, but T2 was presented as the last item in the RSVP stream and was therefore unmasked. Both Giesbrecht and Di Lollo (1998) and Vogel and Luck have shown no accuracy reduction at short lags when T2 was unmasked and presented as the last item in an RSVP stream. Therefore, T2 accuracy was expected to be high at both lags. However, the $P3_{dw}$ to T2 was expected to be delayed at short T1–T2 separations compared with long T1–T2 separations, which would replicate the findings of Vogel and Luck.

Method

Participants. Fifteen right-handed Brock University undergraduate students (10 females) participated for course credit or small monetary payment. All of the participants in this and all experiments included here were between the ages of 18 and 28 and reported no neurological conditions; normal hearing; and normal (or corrected-to-normal) vision. Data from two of the participants in this experiment could not be included in the analysis because they produced

no clearly discernible $P3_{dw}$ for at least one of the lags. In this and all experiments reported here, the majority of the participants who were removed prior to analysis for a failure to show a $P3_{dw}$ for at least one lag, did indeed show what appeared to be P3s in the waves prior to subtraction, but these P3s simply did not vary with the probability manipulation. It is possible that a probability manipulation on one of the tasks may be less salient in the context of performing dual tasks, as opposed to a single task.

Design. The design was a 2 (T1–T2 lag) × 2 (T2 X/not-X) factorial. Lag (T2 appearing as the 3rd or 8th item after T1) and T2 identity (X/not-X) were within-participants variables. Levels varied randomly within blocks, such that T2 was not an X on 80% of trials and was an X on 20% of trials, and each lag occurred equally often for each T2 identity condition every 20 trials. Each participant performed 720 experimental trials in a single session, with a break after 360 trials.

Stimuli. On each trial, an RSVP stream and a rapid auditory presentation (RAP) stream were presented to the participants. In all four experiments reported herein, the participants received both streams, for consistency across experiments. The participants in the present experiment were told to simply ignore the auditory stream and focus on the visual stream. The streams were presented simultaneously, but the identity of the stimulus items presented in the two streams were independent, so that a participant could not use one stream for assistance with performance on another stream. Each stream contained 18 stimuli, presented rapidly, one after another, with an SOA of 90 msec.

The visual stream held 16 distractor letters, one T1 digit target, and T2, which was either an X (20% of the trials) or any other random distractor letter (80% of the trials). T2 was always the last (18th) item in the stream. T1 was presented as either the 15th item (lag 3) or the 10th item (lag 8) in the stream. Visual distractors were randomly chosen from all letters of the alphabet except I, O, and X. The T1 digit was randomly chosen from the set 1, 2, 3, or 4, with the four digits occurring equally often every 8 trials. All visual items were presented in bold, 18-point, black Courier New font (approximately 1.1° of visual angle) in the center of a light gray background. Each stream item was presented for 90 msec, with no interstimulus interval (ISI) prior to the next item in the stream.

The auditory stream comprised 18 distractor letters, with no digit and no X presented on any stream. Distractors were randomly chosen from all letters of the alphabet except the letters W and X.

The auditory stimuli were recordings of spoken letters presented in compressed speech. To create the stimuli, digitized vocal recordings of a male voice were collected using an Apple microphone and a Power Macintosh AV computer. Recordings were made using 16 bits of resolution, for amplitude, at a sampling rate of 47 kHz, with the aid of SoundEdit 16 software. Each letter was then edited and compressed to 85 msec, with a 5 msec ISI between letters. During the experiment, sounds were presented as wave files with 16 bits of resolution, through speakers placed immediately to the left and right of the monitor.

Procedure. Each trial began with the presentation of a black fixation cross in the center of the screen for 500 msec, followed by a 500-msec blank interval before the start of the RSVP and RAP streams. The visual and auditory streams began at the same time, ran concurrently, and had the same number of stimuli. The SOA of 90 msec for stimuli in both the visual and auditory streams produced a presentation rate of just over 11 letters/sec per stream. The participants were instructed to identify the lone visual digit, and to decide whether or not the last item in the stream was an X. The participants were instructed to identify the targets as soon as possible after they were presented, but to hold their response until prompted at the end of the stream. The participants were instructed to take their time and make their responses accurately. Two and a half sec after the stream ended, a sentence appeared, asking whether the T1 digit was an odd or even number. The participants pressed the 1 key, labeled *odd*, or the 2 key, labeled *even*, using their left hand. Immediately after mak-

ing their digit response, a sentence appeared, asking whether the last item was or was not an X. The participants pressed the 9 key, labeled *X*, or the 0 key, labeled *not X*, using their right hand. A 1,000-msec ISI followed their T2 response.

   Apparatus and ERP recordings. A Sony VAIO desktop PC with 17-in. color monitor, running E-Prime (Schneider, Eschman, & Zuccolotto, 2002), was used to present stimuli and record behavioral responses. Neuroscan software running on a Dell Pentium III was used to acquire and analyze electroencephalographic (EEG) data recordings from 64 sites (using a cap from Electrocap International), referenced to linked earlobes. Electro-oculogram (EOG) recordings were made by affixing electrodes to the outer canthi of each eye and the top and bottom of the orbit of both eyes. Signals were amplified with a band-pass of 0.15 to 30 Hz, and digitized at a rate of 500 Hz. ERPs were time-locked to the onset of T2. Epochs were created that began 200 msec prior to T2 presentation and ended 1,000 msec after T2 presentation. Trials with eye-blink artifacts were corrected offline, during analysis, using Neuroscan software. The algorithm calculates the amount of covariation between each EEG channel and a vertical EOG channel and removes the EOG from each EEG electrode on a sweep-by-sweep, point-by-point basis to the degree that the EEG and EOG covaried. If this correction appeared insufficient for a given trial, then the trial was removed by hand prior to averaging. Across all participants in this study, an average of 6.69% of trials were removed prior to averaging (most because of blinks, the rest because of movement artifacts or amplifier anomalies). Trials with incorrect T1 and/or T2 responses were also removed. Data was low-pass filtered at 30 Hz before averaging. Each participant's average waveform on the frequent not-X trials was subtracted from their average waveform on infrequent X trials producing $P3_{dw}$s time-locked to T2 that were uncontaminated by T1 processing, or any other brain activation that was not affected by the low versus high manipulation (Luck, 1998). This difference wave approach is advantageous when presenting multiple stimuli in RSVP, given that all targets and distractors will contribute to the pattern of brain activation. Without the use of P3 difference waves, it would be difficult to isolate the ERP components related to a particular target, because these would be obscured by other components from other stimuli (Luck, 1998). The difference wave approach assumes that the only activation differences that should exist for frequent and infrequent trials are those that are sensitive to the target frequency manipulation. Thus, activation from all other targets and distractors should be equal, as should early activation from the critical target (activation occurring prior to identification and categorization operations). If this assumption

is true, then all activation not due to the critical target manipulation should approximate zero after the subtraction, thereby isolating the $P3_{dw}$ to the critical target (Luck, 1998).

Results

   ERPs. Grand average $P3_{dw}$s to T2, recorded from the midline parietal site (Pz), where the $P3_{dw}$ was largest and is typically reported, are presented in Figure 1 for each lag. Visual inspection of Figure 1 suggests that the $P3_{dw}$ was smaller, started later, and peaked later at lag 3 when compared with lag 8. For all experiments, $P3_{dw}$ latencies were estimated using fractional area latency analyses to capture different "moments" of the waveform. The latency at which a half of the $P3_{dw}$ component's area had been achieved was used as the primary latency measure. This fractional area procedure was used by Vogel and Luck (2002), and fractional area measures are often less susceptible to noise than peak latency. However, when peak latency (latency of highest positive amplitude) was used as the dependent variable, the same patterns were always observed.[1] $P3_{dw}$ latency for T2 was significantly longer when T2 was presented at lag 3 (625 msec) than when T2 was presented at lag 8 (554 msec) [$t(12) = 2.73$, $p < .05$]. As suggested by Figure 1, the $P3_{dw}$ also started 98 msec later when T2 was shown at lag 3 than when T2 was shown at lag 8 [$t(12) = 2.31$, $p < .05$], where the start point was defined as the time point at which 15% of the $P3_{dw}$ component's area had been achieved. When the end point was defined as the time point at which 85% of the $P3_{dw}$ component's area had been achieved, the $P3_{dw}$ was also found to end 53 msec later for lag 8 than for lag 3 [$t(12) = 3.27$, $p < .01$]. The peak amplitude (maximum amplitude) and mean amplitude (average amplitude from start to finish) of the $P3_{dw}$ were both smaller for lag 3 than for lag 8 [$t(12) = 2.66$, $p < .05$, for peak amplitude, and $t(12) = 2.72$, $p < .05$, for mean amplitude].

   Behavior. T2 accuracy (97.2% and 97.8% correct for lag 3 and lag 8, respectively) did not vary as a function of
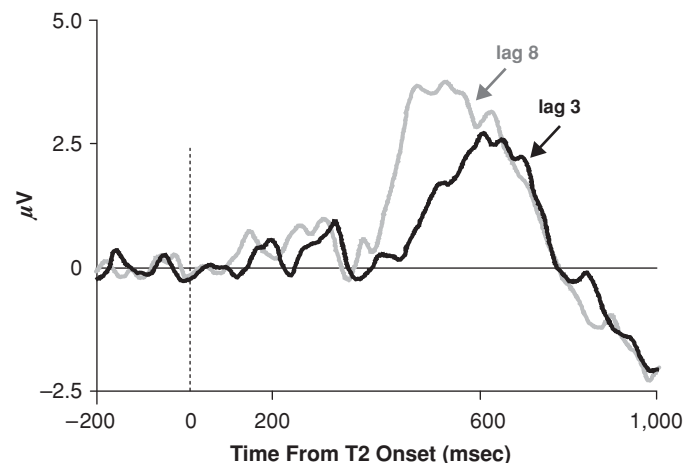

Figure 1. Grand average T2 difference waves (infrequent T2 − frequent T2) from site Pz in Experiment 1 (visual modality), plotted separately for each lag. Note that positive is plotted upward against convention.

lag [$t(12) = 1.61, p > .13$]. T1 digit accuracy (93.2% and 91.6%, respectively) was also not significantly influenced by lag [$t(12) = 1.26, p > .23$].

Discussion

As expected, no AB was observed, given that T2 was unmasked. Indeed, T2 accuracy shows a potential ceiling effect, with accuracy over 95% at both lags. Also as expected, the P3$_{dw}$ for T2 was delayed at short lags when compared with long lags, replicating the results of Vogel and Luck (2002). Vogel and Luck observed a P3$_{dw}$ latency difference of 104 msec, which is similar to the 98-msec difference observed here for start time, and not drastically different from the 71-msec difference observed here with the fractional area measure. Thus, just as in Vogel and Luck, P3$_{dw}$ latency and start times were delayed at short lags. Both results provide evidence that T2 identification and categorization operations are delayed at short lags. As such, these results fit nicely with bottleneck models (Chun & Potter, 1995; Jolicœur, 1999), which propose that consolidation/conscious encoding of T2 is delayed until consolidation/conscious encoding of T1 has been completed.

However, whereas Vogel and Luck (2002) found that the amplitude of the P3$_{dw}$ was not reduced at short lags when compared with long lags, the present results do show an amplitude reduction at the short lag. The P3$_{dw}$ amplitude reduction at short lags will be discussed further in the General Discussion.

EXPERIMENT 2

Both the results of Vogel and Luck (2002) and those of Experiment 1 provide evidence that the P3$_{dw}$ to T2 is delayed at short target–target lags in a modified visual AB paradigm in which T2 is unmasked. In Experiment 2, we present T1 and T2 auditorily and examine whether a P3$_{dw}$ latency difference can be observed outside the visual modality. Finding that T2 P3$_{dw}$ latency is longer at shorter lags than at longer lags would provide evidence that auditory as well as visual information is susceptible to the consolidation bottleneck. In turn, this would provide some support for a common underlying processing limitation for visual and auditory ABs. Finding no T2 P3$_{dw}$ latency difference across lags with auditory stimuli would support arguments for the uniquely visual nature of the consolidation bottleneck and the AB.

Method

Participants. Twenty-two right-handed Brock University undergraduate students (16 females) participated for course credit or small monetary payment. None had participated in Experiment 1. Data from 10 of the participants could not be included in the analysis because they produced no clearly discernible P3$_{dw}$ in at least one of the two SOA conditions.

Stimuli and Procedure. All stimuli and procedures were the same as those used in Experiment 1, with the following exceptions. The visual stream now contained only distractor letters. T1 and T2 replaced two letter distractors in the auditory stream. T1 was a randomly chosen spoken digit (1, 2, 3, or 4) presented as stream item 15 (lag 3) or stream item 10 (lag 8). To facilitate detection, the digit was presented in a slightly higher pitch than the distractors, but was played at the same rate and amplitude as the spoken distractor letters. T2 was the last (18th) item in the stream. On 20% of the trials, T2 was a Z, and on 80% of the trials, T2 was a random distractor letter. The participants were instructed to ignore the visual stream, report whether the lone auditory digit was even or odd, and report whether the last auditory item was a Z or not a Z. Responses were made as in Experiment 1.

Results

ERPs. Grand average T2 P3$_{dw}$s from the midline parietal site (Pz) are presented in Figure 2 for each lag. Again, the T2 P3$_{dw}$ component appears to be later for lag 3 than for lag 8. Indeed, P3$_{dw}$ latency for T2 was 82 msec later when T2 was presented at lag 3 (598 msec) than when T2 was presented at lag 8 (516 msec) [$t(11) = 3.85, p < .01$] and the P3$_{dw}$ started 79 msec later when T2 was shown at lag 3 than when T2 was shown at lag 8 [$t(11) = 3.89, p <$
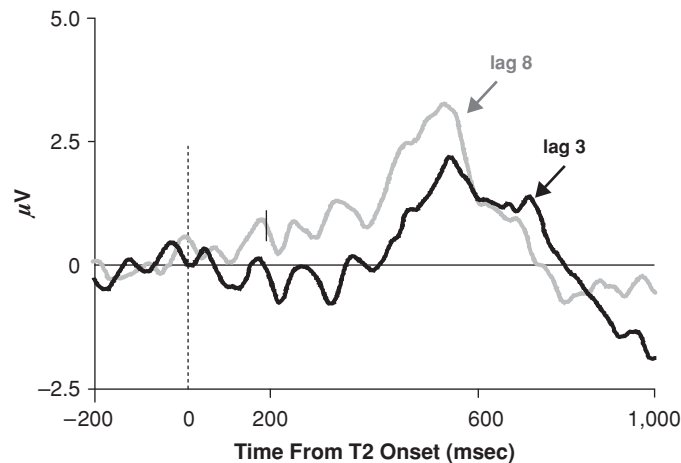

Figure 2. Grand average T2 difference waves (infrequent T2 − frequent T2) from site Pz in Experiment 2 (auditory modality), plotted separately for each lag.

.01]. There was no difference in the end time of the $P3_{dw}$ for lags 3 and 8 [$t(11) = 1.41, p > .18$]. Comparisons of peak amplitude and mean amplitude for lags 3 and 8 produced only marginally significant amplitude differences [$t(11) = 1.92, p < .10$] for peak amplitude, and [$t(11) = 2.07, p < .10$] for mean amplitude.

The $P3_{dw}$ latency difference across lags was compared for Experiment 1 and Experiment 2. A 2 (Experiment 1 or 2) $\times$ 2 (lag 3 or 8) mixed-model ANOVA was performed on the $P3_{dw}$ latencies. A significant main effect of lag was observed [$F(1,23) = 20.29, p < .001$], where $P3_{dw}$ latency was longer at lag 3 than at lag 8, but no main effect of experiment [$F(1,23) = 1.30, p > .26$]. Importantly, the experiment $\times$ lag interaction did not approach significance ($F < 1$), indicating an equivalent $P3_{dw}$ latency difference in both experiments.

Behavior. T2 accuracy did not differ for lag 3 (90.0%) and lag 8 (90.5%) [$t(11) = 1.19, p > .05$], nor did T1 digit accuracy (96.1% and 95.4%, respectively) [$t(11) = 1.96, p > .05$].

Discussion

As in Experiment 1, no AB was observed with an unmasked T2, and T2 accuracy was near ceiling. Both Giesbrecht and Di Lollo (1998) and Vogel and Luck (2002) observed no T2 accuracy reductions at short lags (i.e., no AB) when a visual T2 was unmasked. The present results extend this finding to the auditory modality. The $P3_{dw}$ latency results from Experiment 2 also match those from Experiment 1, in that the $P3_{dw}$ to T2 was delayed at lag 3 when compared with lag 8. Furthermore, the magnitude of the $P3_{dw}$ latency difference across lags was statistically equivalent in the two experiments. These results suggest that identification and categorization of T2 are also delayed when both targets are auditory, and provide support for a common processing bottleneck for visual and auditory dual-task costs. There was a trend toward $P3_{dw}$ amplitude reduction at lag 3 in the present experiment, and the difference in amplitudes between lags was numerically larger here than in Experiment 1, but it failed to reach statistical significance due to the greater variability in $P3_{dw}$ size across participants in the present experiment.

EXPERIMENT 3

The results of Experiments 1 and 2 suggest that the processing of T1 delays the identification/categorization operations of T2 in both the visual modality and the auditory modality. In Experiments 3 and 4, we examined whether the $P3_{dw}$ to T2 would be delayed at short target–target separations when the first target was visual and the second target was auditory (Experiment 3) and when the first target was auditory and the second target was visual (Experiment 4). If both experiments show T2 $P3_{dw}$ delays at lag 3 in comparison with lag 8, then this would provide evidence that identification and categorization of T2 are delayed even when targets are presented cross-modally, and would support models suggesting that a common

mechanism underlies within-modality and cross-modality AB patterns. However, if these two experiments show no T2 $P3_{dw}$ difference for lags 3 and 8, this would suggest that the bottleneck on stimulus consolidation is modality specific, and would argue against a common mechanism for within-modality and cross-modality AB.

Method

The participants were 20 right-handed Brock University undergraduate students (13 females) from the same participant pool as above. None of the 20 had participated in Experiments 1 or 2. Ten of the participants produced no discernible $P3_{dw}$ in at least one of the two SOA conditions and were removed from the analysis.

All stimuli and procedures were the same as those used in Experiment 2, with the following exceptions. The T1 digit was removed from the auditory stream and replaced with a random distractor letter. The T1 digit was now presented in the visual stream, as in Experiment 1. T2 was still the last (18th) item in the auditory stream, as in Experiment 2. The participants were instructed to report whether the lone digit in the visual stream was even or odd, and report whether the last auditory item was a Z or not a Z.

Results

ERPs. Grand average T2 $P3_{dw}$s from the midline parietal site (Pz) are presented in Figure 3 for each lag. As before, the T2 $P3_{dw}$ component appears to be later for lag 3 than for lag 8. Analysis confirmed that the $P3_{dw}$ latency for T2 was 82 msec later when T2 was presented at lag 3 (639 msec) than when T2 was presented at lag 8 (557 msec) [$t(9) = 3.21, p < .05$], and the $P3_{dw}$ started 83 msec later when T2 was shown at lag 3 than when T2 was shown at lag 8 [$t(9) = 3.00, p < .05$]. The $P3_{dw}$ also ended significantly later for lag 3 than for lag 8 [$t(9) = 3.27, p < .05$]. Peak amplitude and mean amplitude did not differ for lags 3 and 8 ($ts < 1$).

The $P3_{dw}$ latency difference across lags was compared for Experiment 3 and Experiment 2. The auditory T2 was identical in these two experiments, but was preceded by a within-modality target in Experiment 2 and a cross-modality target in Experiment 3. The 2 (Experiment 2 or 3) $\times$ 2 (lag 3 or 8) mixed ANOVA produced a significant main effect of lag [$F(1,20) = 24.77, p < .001$], where $P3_{dw}$ latency was longer at lag 3 than at lag 8, no main effect of experiment [$F(1,20) = 1.52, p > .23$], and no experiment $\times$ lag interaction ($F < 1$), indicating an equivalent $P3_{dw}$ latency difference in both experiments.

Behavior. There was a small but significant difference in T2 accuracy for lag 3 (90.1%) and lag 8 (91.1%) [$t(11) = 2.30, p < .05$]. T1 digit accuracy did not differ for lag 3 (91.7%) and lag 8 (91.2%) [$t(11) = 1.02, p > .33$].

Discussion

The results of Experiment 3, with cross-modality targets, replicate those of Experiments 1 and 2, with within-modality targets. T2 accuracy was high at both lags, but the T2 $P3_{dw}$ was delayed at lag 3 when compared with lag 8, providing evidence that identification/categorization operations for T2 are delayed at short target separations even when processing a cross-modal T1.
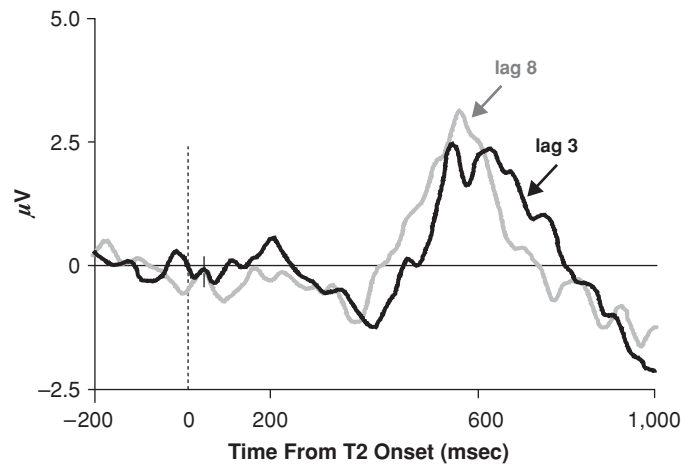
Figure 3. Grand average T2 difference waves (infrequent T2 − frequent T2) from site Pz in Experiment 3 (visual T1 and auditory T2), plotted separately for each lag.

EXPERIMENT 4

In Experiment 3, $P3_{dw}$ latency delays were observed at short lags when T1 was visual and T2 was auditory. In Experiment 4, the possibility for $P3_{dw}$ latency delay is examined with the reverse modality ordering (auditory T1 and visual T2).

Method

Participants were 26 Brock undergraduate students (19 females) from the same research pool as above. None had participated in Experiments 1–3. Nine participants failed to show a clear $P3_{dw}$ in at least one of the modality conditions, and were therefore removed prior to analysis.

The stimuli and procedures were the same as those employed in Experiment 3, with the following exceptions. The digit T1 was removed from the visual stream and added to the auditory stream, just as in Experiment 2.[2] T2 was removed from the auditory stream and added as the last item in the visual stream, just as it appeared in

Experiment 1. Random letter distractors replaced the visual T1 and auditory T2 targets that had been removed. The participants were instructed to report whether the lone auditory digit was even or odd, and whether the last item in the RSVP stream was an X or not an X.

Results

ERPs. Grand average T2 $P3_{dw}$s from the midline parietal site (Pz) are presented in Figure 4 for each lag. The T2 $P3_{dw}$ component again appears to be later in time and smaller for lag 3 than for lag 8. Indeed, the $P3_{dw}$ latency for T2 was 39 msec later when T2 was presented at lag 3 (564 msec) than when T2 was presented at lag 8 (525 msec) [$t(16) = 2.83$, $p < .05$]. In contrast with the results of previous experiments, the $P3_{dw}$ did not start significantly later when T2 was shown at lag 3 than when T2 was shown at lag 8 [$t(16) < 1$] but instead, the $P3_{dw}$ ended 63 msec later at lag 3 than at lag 8 [$t(16) = 4.49$, $p < .001$]. Both peak $P3_{dw}$ amplitude and mean $P3_{dw}$ am-
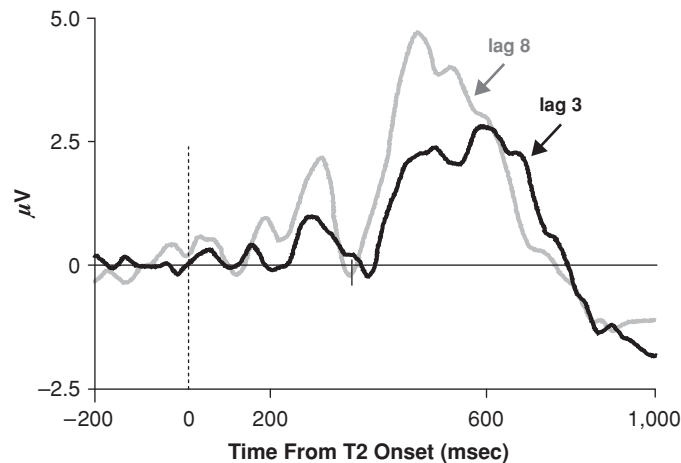

Figure 4. Grand average T2 difference waves (infrequent T2 − frequent T2) from site Pz in Experiment 4 (auditory T1 and visual T2), plotted separately for each lag.

plitude were significantly reduced for lag 3 as compared with lag 8 [$t(16) = 3.18$, $p < .01$, and $t(16) = 3.05$, $p < .01$, respectively].

The P3$_{dw}$ latency difference across lags was also compared for Experiment 4 and Experiment 1. The visual T2 was identical in these two experiments, but was preceded by a within-modality target in Experiment 1 and a cross-modality target in Experiment 4. The 2 (Experiment 4 or 1) $\times$ 2 (lag 3 or 8) mixed ANOVA produced a significant main effect of lag [$F(1,28) = 15.86$, $p < .001$], with longer latencies at the shorter lag, and a marginally significant main effect of experiment [$F(1,28) = 4.11$, $p < .08$], whereby the P3$_{dw}$ latency was longer overall in Experiment 1. Of primary interest was the absence of the experiment $\times$ lag interaction [$F(1,28) = 1.31$, $p > .26$], indicating a statistically equal P3$_{dw}$ latency difference in both experiments.

Behavior. T2 accuracy did not differ for lag 3 (97.5%) and lag 8 (97.4%) ($t < 1$), nor did T1 digit accuracy for lag 3 (82.2%) and lag 8 (81.0%) [$t(16) = 1.59$, $p > .46$].

P3 latency across all of the experiments. Mean P3 latencies from Experiments 1 through 4 are shown in Figure 5 as a function of target modality combination and lag. A 2 (lag 3 or 8) $\times$ 2 (T1 visual or auditory) $\times$ 2 (T2 visual or auditory) ANOVA was performed on P3$_{dw}$ latencies to examine whether the modality of T1, the modality of T2, or their interaction modulated the difference in P3$_{dw}$ latency across the lags. The results showed a significant main effect of lag [$F(1,48) = 40.94$, $p < .001$], where P3$_{dw}$ latencies were longer at lag 3 than at lag 8, and a significant main effect of T1 modality [$F(1,48) = 5.01$, $p < .05$], where the overall P3$_{dw}$ to T2 appeared later when T1 was visual than when T1 was auditory. There was no significant effect of T2 modality ($F < 1$), nor was there a significant T1–T2 modality interaction ($F < 1$). Most importantly, there was no significant interaction that included the lag variable [$F < 1$ for lag $\times$ T1 modality, and

for the three-way interaction; $F(1,48) = 1.58$, $p > .21$ for lag $\times$ T2 modality], suggesting that the amount of P3$_{dw}$ latency delay at short lags was not influenced by the modality combination of the targets.

A 2 (lag 3 or 8) $\times$ 2 (T1 visual or auditory) $\times$ 2 (T2 visual or auditory) ANOVA was performed on P3$_{dw}$ peak amplitudes to examine whether the modality of T1, the modality of T2, or their interaction modulated the difference in P3$_{dw}$ amplitude across the lags. The results showed a significant main effect of lag, where the overall P3$_{dw}$ peak amplitude for T2 was smaller at lag 3 than at lag 8 [$F(1,48) = 12.39$, $p < .001$]. None of the interactions that included the lag variable approached significance [$F < 1$ for lag $\times$ T2 modality; $F(1,48) = 1.18$, $p > .28$, for the three-way interaction; and $F(1,48) = 1.82$, $p > .18$, for lag $\times$ T1 modality]. Peak P3$_{dw}$ amplitude for T2 was marginally larger for visual T2s than for auditory T2s [$F(1,48) = 3.13$, $p > .08$], but did not differ as a function of T1 modality, or for the interaction of T1 and T2 modality (both Fs < 1).

Discussion

As in previous experiments, T2 accuracy was high for both lags, but P3$_{dw}$ latency was longer for lag 3 than for lag 8. In previous experiments, the start time of the P3$_{dw}$ had also been significantly delayed at lag 3, when compared with lag 8, but this was not true in the present experiment. Instead, the end of the P3$_{dw}$ was significantly delayed in the present study. T1 accuracy was somewhat lower in the present study than in the other experiments. When participants made an error on T1, it was usually because they missed it altogether rather than mistaking one digit for another. On trials in which T1 was missed, T2 should have been processed on time, because there would be no bottleneck. It is possible, therefore, that T1 misses on some trials slightly (but not significantly) reduced the P3$_{dw}$ latency difference between the lags, and the P3$_{dw}$ start time difference.
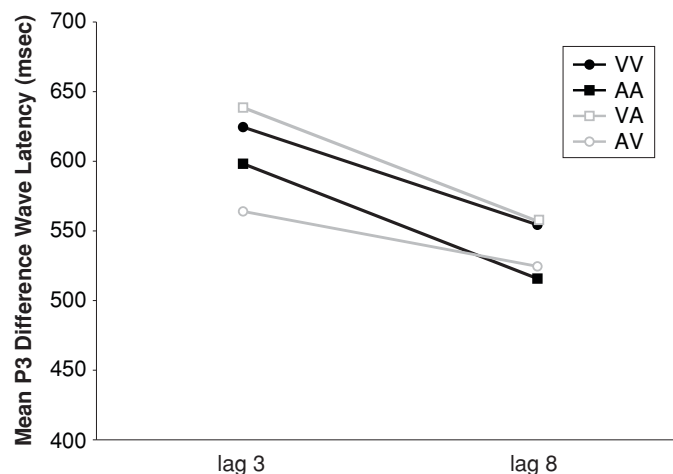

Figure 5. Mean P3$_{dw}$ latency as a function of target modality combination and lag, using data from Experiments 1 through 4.

GENERAL DISCUSSION

Summary

In each of the experiments, T1 was embedded in an RSVP or RAP stream and was therefore masked, whereas T2 was the last item in a stream and therefore unmasked. In all four experiments, the $P3_{dw}$ time-locked to T2 was found to be significantly delayed (an average of 69 msec) when T2 was presented soon after T1 (lag 3), compared with when T1 and T2 were presented farther apart (lag 8). This $P3_{dw}$ delay at the short lag was observed when both targets were presented visually (replicating Vogel & Luck, 2002), when both targets were presented auditorily, and when targets were presented cross-modally. Furthermore, the modality of T1, the modality of T2, or the T1–T2 modality combination did not dramatically nor statistically influence the duration of the T2 $P3_{dw}$ delay at the short lag. Overall peak amplitude for the $P3_{dw}$ time-locked to T2 was also reduced slightly at lag 3 ($3.75\ \mu V$) relative to lag 8 ($4.71\ \mu V$), and this amplitude difference across lags was also not influenced dramatically by the target modality combination.

Implications for AB Theories

The present results provide support for models that explain the AB in terms of a bottleneck on stimulus consolidation in working memory (see, e.g., Chun & Potter, 1995; Jolicœur, 1999). According to these models, T1 consolidation takes time, and if T2 is presented while T1 is being consolidated, then T2 consolidation must wait. If the stage 1 perceptual representation of T2 cannot outlast the wait period, then T2 consolidation will fail, and an AB will be observed (Vogel et al., 1998). However, if the stage 1 perceptual representation of T2 can outlast the wait period, then T2 consolidation will simply happen later, and no AB will be observed.

Finding T2 $P3_{dw}$ delays at short lags when both targets were auditory, and when one target was auditory and the other was visual, provides evidence that this bottleneck on working memory consolidation is not specific to vision, and is amodal in nature. This supports Jolicœur and colleagues' consolidation bottleneck model of the AB, in which the consolidation bottleneck is viewed as a central and amodal processing limitation (Jolicœur, 1998, 1999; Jolicœur & Dell'Acqua, 1998, 1999). Chun and Potter's (1995) two-stage model of the AB could also accommodate the results without modifications, although these authors have argued that the AB is uniquely visual in nature and that auditory and cross-modal AB findings reflect task-switch artifacts (Potter et al., 1998). In contrast to arguments suggesting that auditory and/or cross-modal AB patterns are manifestations of different processing limitations than those that underlie ABs with visual targets (see, e.g., Potter et al., 1998; Soto-Faraco & Spence, 2002), the present results suggest that visual, auditory, and cross-modal ABs result from a common bottleneck on working memory consolidation operations, at least in part. Even if one does not want to conceptualize the $P3_{dw}$ as reflecting working memory consolidation, the same pattern of

$P3_{dw}$ latency delay for each of the modality combinations suggests that a common processing limitation underlies the AB patterns in the four visual/auditory target combinations. However, it should be noted that the P3 reflects the output of a number of preceding stages of processing. Thus, a delay in any of the earlier stages could simply feed forward to produce a delay in the P3. There is evidence of little or no delay or suppression at earlier processing stages when both targets are visual (Vogel et al., 1998), but there have been no investigations of earlier components for auditory and cross-modal ABs. As such, it is possible that, even though the P3 is found to be delayed in each experiment, the $P3_{dw}$ delays observed in Experiments 2, 3, and 4 could result from a delay at an earlier processing stage than was observed in Experiment 1. It should be noted, however, that visual comparison of the P3 waves prior to the subtractions used to create the difference wave showed no evidence of this.

If the duration of the T2 $P3_{dw}$ delay at short lags does not differ for visual, auditory, and cross-modality target pairs, then why are visual ABs typically larger and more robust than auditory or cross-modality AB effects? As discussed earlier, one possibility is that auditory targets are simply more difficult to effectively mask due to the relatively large capacity and long duration of echoic memory. A visual target is effectively masked by a single visual backward pattern mask (Duncan et al., 1994; Giesbrecht & Di Lollo, 1998; Vogel & Luck, 2002), whereas an entire sequence of auditory material may survive for several seconds in echoic memory (Cowan, 1984). Indeed, because T2 was never masked in these experiments, it is impossible to determine the size of the ABs that would be expected in each experiment, and to know whether or not an AB would have even been observed for all experiments. Even if T2 had been masked on some trials in the present study, little or no AB may have been observed for Experiments 2–4 if participants were able to recover an auditory T1 or T2 offline using the stage 1 perceptual representation that was maintained. Therefore, using T2 accuracy alone, one cannot discriminate whether T2 was processed on time without encountering a bottleneck, or whether T2 encountered a processing bottleneck, but was fully processed later using the echoic trace. However, when one measures the $P3_{dw}$ and/or the RT to T2 one is able to see that even in the presence of high T2 accuracy, T2 processing is delayed (Arnell & Duncan, 2002; Arnell et al., 2004; Jolicœur & Dell'Acqua, 1998, 1999). Whereas the RT delay could reflect a delay in later processing operations such as response selection, the $P3_{dw}$ delay provides good evidence for a delay in T2 processing operations that follow stimulus identification and categorization, but precede response selection—of which a likely possibility is working memory consolidation (see, e.g., Donchin, 1981). Thus, the visual, auditory, and cross-modality AB effects may reflect the common underlying processing limitation, at least in part, but visual targets may be more likely to require online processing, and therefore more readily set off an AB when they are presented as T1, and be less able to circumvent limitations when they are presented as T2.

This is not to suggest that there are no within-modality processing limitations that also contribute to the AB size when T2 is masked. For example, there may be within-modality and task-interference effects (see, e.g., Shapiro, Raymond, & Arnell, 1994) that contribute to within-modality, but not cross-modality, AB effects (Arnell & Duncan, 2002). However, the present results do suggest that to the extent that limitations on working memory consolidation contribute to the AB, the AB appears to be a manifestation of an amodal processing limitation.

T2 $P3_{dw}$ amplitude was reduced somewhat at lag 3 in the present experiments. This reduction in amplitude at lag 3 was not simply the result of a $P3_{dw}$ that was flattened but spread out over a longer time window, which might have been expected if there was simply more variability in the timing of cognitive operations, trial to trial or participant to participant. As mentioned previously, $P3_{dw}$ amplitude has been shown to be attenuated at short lags in the standard AB paradigm in which T2 is masked (Vogel et al., 1998). However, in the standard AB paradigm, the $P3_{dw}$ amplitude attenuation is more dramatic (the $P3_{dw}$ is almost absent), and the attenuation accompanies a T2 accuracy reduction at short lags (i.e., an AB). In contrast, here T2 accuracy is almost identical at lags 3 and 8, which suggests that participants did not simply miss T2 on some trials. The reduced T2 $P3_{dw}$ amplitude at short lags was not observed by Vogel and Luck (2002) with unmasked T2s, but has been observed by Luck (1998), Arnell et al. (2004), and Hoffman, Houck, MacMillan, Simons, and Oatman (1985) when T2 required a speeded response. Indeed, Hoffman et al. suggested that P3 amplitude reflected the amount of a limited capacity resource that is separate from a resource concerned with motor responses. Following Hoffman et al.'s assumption, one would conclude that the consolidation of T2 is not only delayed at short lags, but may also have fewer processing resources brought to bear.

Dual-Task Costs

Many studies have shown RT delays to unmasked T2s that follow cross-modal masked T1s in hybrid AB–PRP tasks (Arnell & Duncan, 2002; Jolicœur & Dell'Acqua, 1998, 1999), and it is tempting to use them as support for delayed T2 consolidation. However, although it was clear that T2 RTs were delayed in these studies, it was not clear whether T2 consolidation was delayed per se, because the use of a speeded T2 response meant that T2 RTs may have been delayed at later stages, such as response selection. Therefore, whereas behavioral measures of T2 accuracy and response time do not allow us to track the timing of T2 identification and consolidation, the $P3_{dw}$ does. Indeed, tracking the latency of the T2-time-locked $P3_{dw}$ component provides a useful way to examine the timing of T2 consolidation. For example, Arnell et al. (2004) asked participants to make an unspeeded response to a masked visual T1 (just as in the AB), and a speeded response to an unmasked auditory T2 (just as in the psychological refractory period or PRP paradigm). They observed that the T2

$P3_{dw}$ was significantly delayed at short lags, when compared with long lags, and that the amount of $P3_{dw}$ delay was almost equal to the amount of T2 RT delay at short lags. These results suggested that even though the T2 response was speeded, the RT delays at short lags did represent delays on stimulus consolidation. Thus, the present results are consistent with those of Arnell et al., and together, they suggest that as long as T1 is masked, T2 consolidation will be delayed, regardless of whether T2 requires a speeded response or an unspeeded response.

However, when Arnell et al. (2004) presented an unmasked T1 and an unmasked T2 that each required a speeded response (as in the PRP paradigm), the T2 $P3_{dw}$ latency delay decreased and the T2 RT delay increased, such that the $P3_{dw}$ delay now represented only a small fraction of the total RT delay. This pattern was also observed by Luck (1998), using the PRP paradigm. The fact that both studies found that the majority of RT delay at short lags could not be accounted for by the magnitude of the P3 delay at short lags suggests that the majority of interference in the PRP paradigm happens after stimulus consolidation. Indeed, Osman and Moore (1993) showed that, as with RTs, the lateralized readiness potential (LRP) time-locked to T2 presentation was substantially delayed at short lags in the PRP paradigm. The LRP is largest over the hemisphere contralateral to the hand used for response, and is sensitive to response selection and motor-preparation operations (Coles, 1989; Kutas & Donchin, 1980). Finding commensurate target-locked LRP delays at short SOAs suggests that the PRP slowing resulted primarily from a bottleneck at or before response selection or movement preparation. Thus, across studies, the results suggest that there is an amodal bottleneck on stimulus consolidation operations, and a separate amodal bottleneck on response-selection operations.

Conclusions

The present results provide support for an amodal bottleneck on stimulus consolidation into working memory. These results are consistent with theories suggesting that an amodal bottleneck on stimulus consolidation underlies the AB effect, at least in part (see, e.g., Jolicœur, 1999). The present results are also consistent with results from hybrid AB–PRP paradigms in which a masked T1 results in P3 and T2 RT delays for cross-modal T2s at short lags (Arnell et al., 2004). Indeed, T2 RT slowing observed in cross-modal hybrid AB–PRP paradigms can now be explained in terms of memory consolidation bottlenecks without the need to invoke additional later response-selection confusion, and without suggesting that stimulus consolidation and response-selection operations share a common processing bottleneck (see, e.g., Jolicœur, 1999). T2 stimulus consolidation will be delayed when T1 requires online stimulus consolidation, whether T1 and T2 are from the same modality or a different modality. If T1 and T2 both require speeded responses, then an additional, but dissociable, bottleneck on response-selection operations will be encountered if the response-selection demands are sufficiently high.

REFERENCES

ANDERSON, A. K. (2005). Affective influences on the attentional dynamics supporting awareness. *Journal of Experimental Psychology: General*, **134**, 258-281.

ARNELL, K. M., & DUNCAN, J. (2002). Separate and shared sources of dual-task cost in stimulus identification and response selection. *Cognitive Psychology*, **44**, 105-147.

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.

ARNELL, K. M., & JENKINS, R. (2004). Revisiting within-modality and cross-modality attentional blinks: Effects of target-distractor similarity. *Perception & Psychophysics*, **66**, 1147-1161.

ARNELL, K. M., & JOLICŒUR, P. (1999). The attentional blink across stimulus modalities: Evidence for central processing limitations. *Journal of Experimental Psychology: Human Perception & Performance*, **25**, 630-648.

ARNELL, K. M., & LARSON, J. M. (2002). Cross-modality attentional blinks without preparatory task-set switching. *Psychonomic Bulletin & Review*, **9**, 497-506.

BROADBENT, D. E., & BROADBENT, M. H. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics*, **42**, 105-113.

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 & Performance*, **21**, 109-127.

COLES, M. G. (1989). Modern mind-brain reading: Psychophysiology, physiology, and cognition. *Psychophysiology*, **26**, 251-269.

COWAN, N. (1984). On short and long auditory stores. *Psychological Bulletin*, **96**, 341-370.

DELL'ACQUA, R., JOLICŒUR, P., PESCIARELLI, F., JOB, R., & PALOMBA, D. (2003). Electrophysiological evidence of visual encoding deficits in a cross-modal attentional blink paradigm. *Psychophysiology*, **40**, 629-639.

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

DONCHIN, E., & COLES, M. G. (1988). Is the P300 component a manifestation of context updating? *Behavioral & Brain Sciences*, **11**, 357-427.

DUNCAN, J., MARTENS, S., & WARD, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, **379**, 808-810.

DUNCAN, J., WARD, R., & SHAPIRO, K. L. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, **369**, 313-315.

GIESBRECHT, B., & DI LOLLO, V. (1998). Beyond the attentional blink: Visual masking by object substitution. *Journal of Experimental Psychology: Human Perception & Performance*, **24**, 1454-1466.

HILLSTROM, A. P., SHAPIRO, K. L., & SPENCE, C. (2002). Attentional limitations in processing sequentially presented vibrotactile targets. *Perception & Psychophysics*, **64**, 1068-1081.

HOFFMAN, J. E., HOUCK, M. R., MACMILLAN, F. W., III, SIMONS, R. F., & OATMAN, L. C. (1985). Event-related potentials elicited by automatic targets: A dual-task analysis. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 50-61.

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

JOLICŒUR, P., & DELL'ACQUA, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology*, **36**, 138-202.

JOLICŒUR, P., & DELL'ACQUA, R. (1999). Attentional and structural constraints on visual encoding. *Psychological Research*, **62**, 154-164.

KUTAS, M., & DONCHIN, E. (1980). Preparation to respond as manifested by movement-related brain potentials. *Brain Research*, **202**, 95-115.

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

LUCK, S. J., VOGEL, E. K., & SHAPIRO, K. L. (1996). Word meanings can be accessed but not reported during the attentional blink. *Nature*, **383**, 616-618.

MAGLIERO, A., BASHORE, T. R., COLES, M. G., & DONCHIN, E. (1984). On the dependence of P300 latency on stimulus evaluation processes. *Psychophysiology*, **21**, 171-186.

MONDOR, T. A. (1998). A transient processing deficit following selection of an auditory target. *Psychonomic Bulletin & Review*, **5**, 305-311.

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 & Performance*, **19**, 1292-1312.

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

RAYMOND, J. E., SHAPIRO, K. L., & ARNELL, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception & Performance*, **18**, 849-860.

SCHNEIDER, W., ESCHMAN, A., & ZUCCOLOTTO, A. (2002). *E-Prime user's guide*. Pittsburgh, PA: Psychology Software Tools.

SHAPIRO, K. L., ARNELL, K. M., & RAYMOND, J. E. (1997). The attentional blink. *Trends in Cognitive Sciences*, **1**, 291-296.

SHAPIRO, K. L., CALDWELL, J., & SORENSEN, R. E. (1997). Personal names and the attentional blink: A visual "cocktail party" effect. *Journal of Experimental Psychology: Human Perception & Performance*, **23**, 504-514.

SHAPIRO, K. [L.], DRIVER, J., WARD, R., & SORENSEN, R. E. (1997). Priming from the attentional blink: A failure to extract visual tokens but not visual types. *Psychological Science*, **8**, 95-100.

SHAPIRO, K. L., RAYMOND, J. E., & ARNELL, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 357-371.

SHULMAN, H., & HSIEH, V. (1995, November). *The attentional blink in mixed modality streams*. Paper presented at the 36th Annual Meeting of the Psychonomic Society, Los Angeles.

SOTO-FARACO, S., & SPENCE, C. (2002). Modality-specific auditory and visual temporal processing deficits. *Quarterly Journal of Experimental Psychology*, **55A**, 23-40.

SOTO-FARACO, S., SPENCE, C., FAIRBANK, K., KINGSTONE, A., HILLSTROM, A. P., & SHAPIRO, K. [L.] (2002). A crossmodal attentional blink between vision and touch. *Psychonomic Bulletin & Review*, **9**, 731-738.

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

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 & Performance*, **24**, 1656-1674.

NOTES

1. In Experiment 1, the difference in P3 latency for lag 3 and lag 8 was 71 msec, when using the fractional area latency measure, and 62 msec, when using the peak latency measure. In Experiment 2, the P3 latency difference was 82 msec for the fractional area measure, and 78 msec for peak latency. The P3 latency difference was 82 msec for the fractional area measure and 63 msec for peak latency in Experiment 3, and 39 msec, with the fractional area measure, and 50 msec, with the peak latency measure, in Experiment 4.

2. Arnell and Jolicœur (1999) noticed that when an auditory T1 was presented in a different pitch than the distractors, there was no AB for a visual T2, and the participants reported solving T1 offline. However, when both targets were auditory, T1 was solved online and an AB was observed. Therefore, in Experiment 2, the T1 digit was presented in a slightly higher pitch than the letters, to facilitate T1 identification. However, in Experiment 4, T1 was presented in the same pitch as the letters.