Multitasking Performance Deficits: Forging Some Links Between The Attentional Blink And The Psychological Refractory Period

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This chapter presents new empirical work that bears on the issue of whether multitasking performance deficits are a byproduct of strategic control as opposed to structural capacity limitations. Accuracy in reporting the identity of a masked visual target was measured at various delays following an auditory stimulus that required an immediate speeded response. A larger attentional blink (AB) effect was found when the auditory task had four possible stimuli and response alternatives than when it had only two. In a PRP (psychological refractory period) experiment, two speeded responses were required to stimuli presented in rapid succession. The auditory task that was used as $Task_1$ of the AB experiment was now the second task in the PRP experiment. Effects of number of response alternatives in $Task_2$ were additive with SOA, suggesting that the manipulation had an effect at or after the locus of PRP interference. The results suggest the existence of a locus of AB interference that occurs either at or after a locus of interference causing the PRP effect. Implications for the role of control vs structural limitations are discussed.

Jolicœur.1 INTRODUCTION

This chapter explores the relationship between two popular paradigms that require different responses to two stimuli presented in rapid succession: The PRP paradigm ("psychological refractory period;" see Pashler, 1994, for a review) and the AB paradigm ("attentional blink;" see Shapiro & Raymond, 1994, for a review). In the PRP paradigm, two speeded responses are made in rapid succession, usually to two distinct and unmasked

stimuli. The PRP effect is a slowing of the second response as the stimulus onset asynchrony (SOA) between the two stimuli is reduced. In the AB paradigm, two stimuli are also shown in rapid succession, and usually both are masked. The AB phenomenon is a decrease in report accuracy of the second stimulus at short SOAs.

With some notable exceptions, most researchers have concluded that performance deficits in these paradigms arise because of capacity limitations in central processing mechanisms. These mechanisms are assumed to perform such operations as memory encoding and retrieval, response selection, and other complex cognitive operations that occur after perceptual encoding but before motor output.

Surprisingly, as noted by Monsell (1996), until recently the theoretical discussion of these paradigms has rarely made reference to the issue of control. The debate has focused largely on the locus of interference effects or on the specific combinations of tasks that result in performance limitations. Recently, however, the is-

sue of control has been brought to the fore by theoretical arguments that relate major findings in these both paradigms to causal influences of strategic control. We consider two examples. The first is the EPIC model of the mental architecture and executive functions formulated by Kieras and Meyer (this volume; see also Meyer and Kieras, 1997ab). They explicit reject the proposition that the PRP effect results from structural limitations in central mechanisms. Instead, they propose that dual-task slowing in the PRP paradigm results from adaptive executive control processes that are designed to guarantee that the response to the first stimulus occurs before the response to the second stimulus (subjects are often instructed to perform the responses in this order).

A second example is provided by Potter, Chun, Banks, and Muckenhoupt's (1998) account of cross-modal deficits in the AB paradigm. Potter et al. (1998) found evidence of a cross-modal AB only when a switch in task (Rogers & Monsell, 1995) associated with the first and second targets to be reported was required. Potter et al. (1998) suggest that the AB deficit observed in the cross-modal condition may have a 'strategic' source, such as preparation (see De Jong, this volume; De Jong & Sweet, 1994), different from the structural source of AB interference when the stimuli are presented in the same modality.

In the AB paradigm, the response to the second target stimulus is not speeded. Therefore, the control-based account of Meyer and Kieras (1997ab; Kieras and Meyer, this volume) for dual-task slowing in the PRP paradigm would not appear to apply to the AB paradigm, regardless of whether stimulation is within-modality or between-modality. Given the account proposed by Meyer and Kieras, it would seem most natural to think about PRP and AB effects as two rather different manifestations of multitasking performance deficits. While the PRP effect would reflect central control required to sequence rapid responses, AB effects would presumably be taken to reflect some other form of system overload that occurs at a more peripheral level (e.g., perceptual and/or motor) because, according to the EPIC model, the operations required to perform the AB task are not likely to induce central interference. However, this hypothesis does not agree well with recent results suggesting that the AB effect may be caused by central interference (see section titled "Locus of Factor Effects in PRP and AB Paradigms").

The empirical work presented in subsequent sections explored the relationship between AB and PRP paradigms, and asked whether the sources of these multitasking deficits may share some fundamental functional similarity, which would in turn have implications for the role of control processes in causing these effects. We first consider the interpretation of factor effects in these paradigms.

The Attentional Blink (AB) phenomenon

The AB phenomenon is a decrease in the accuracy of report of a second target (T_2), when that target follows rapidly after a first target (T_1) that must also be reported. The paradigm most commonly used to study the phenomenon embeds the two targets within a stream of other stimuli presented using rapid serial visual presentation (RSVP; e.g., Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992, 1995; Jolicœur, 1998a; but see Duncan, Ward, & Shapiro, 1994).

For example, Jolicœur (1998a, Experiment 1) presented a red first target (T_1, H or S) embedded in an RSVP stream of white letters. The second target (T_2) was an X or a Y. T_2 occurred on every trial, but T_1 was presented on only half of the trials. The most interesting results concern the accuracy of report of the second target. In control trials (T_1-absent), the mean accuracy was about 85%. In the experimental condition (T_1-present), accuracy was at about 73% when T_2 followed T_1 immediately (lag 1), about 64% at lags 2–3, about 71% at lag 4, with a continued recovery to near-baseline levels as lag was increased further. Raymond et al. (1992) referred to the loss of accuracy of report for T_2, as a function of the lag between T_1 and T_2, as an "attentional blink" (AB), and this label is now widely used.

Locus of Factor Effects in PRP and AB Paradigms

Much of the work on the AB phenomenon has focused on two issues:

- Where is the interference between $Task_1$ and $Task_2$ taking place?

- What is the nature of this interference?

This chapter primarily addresses the first issue. Although this issue is not settled, there is a growing consensus that the locus of the interference is relatively late in processing, probably after stimuli have activated semantic-level representations (Shapiro, Driver, Ward, & Sorensen, 1997; Luck, Vogel, & Shapiro, 1996; Jolicœur, 1998a; 1999b; Duncan et al., 1994; Chun & Potter, 1995; see also Jolicœur & Dell'Acqua, 1998abc; Dell'Acqua & Jolicœur, 1998).

The simplest model of dual-task interactions assumes that some mechanisms cannot be shared across two tasks (Welford, 1952). When two tasks both need the same mechanism, interference results — the mechanism constitutes a processing bottleneck. The top stage diagram in Figure Jolicœur.1A represents the processing required to perform the first of two tasks in a PRP paradigm. The presentation of the first target (T_1) triggers the stage(s) labeled A_1. A_1 represents all stages before the bottleneck. Processing stages that require the bottleneck are labeled B_1. Finally, stages after the bottleneck are labeled C_1. The sum of pre-bottleneck, bottleneck, and post-bottleneck stage durations equals the response time in $Task_1$, or RT_1.

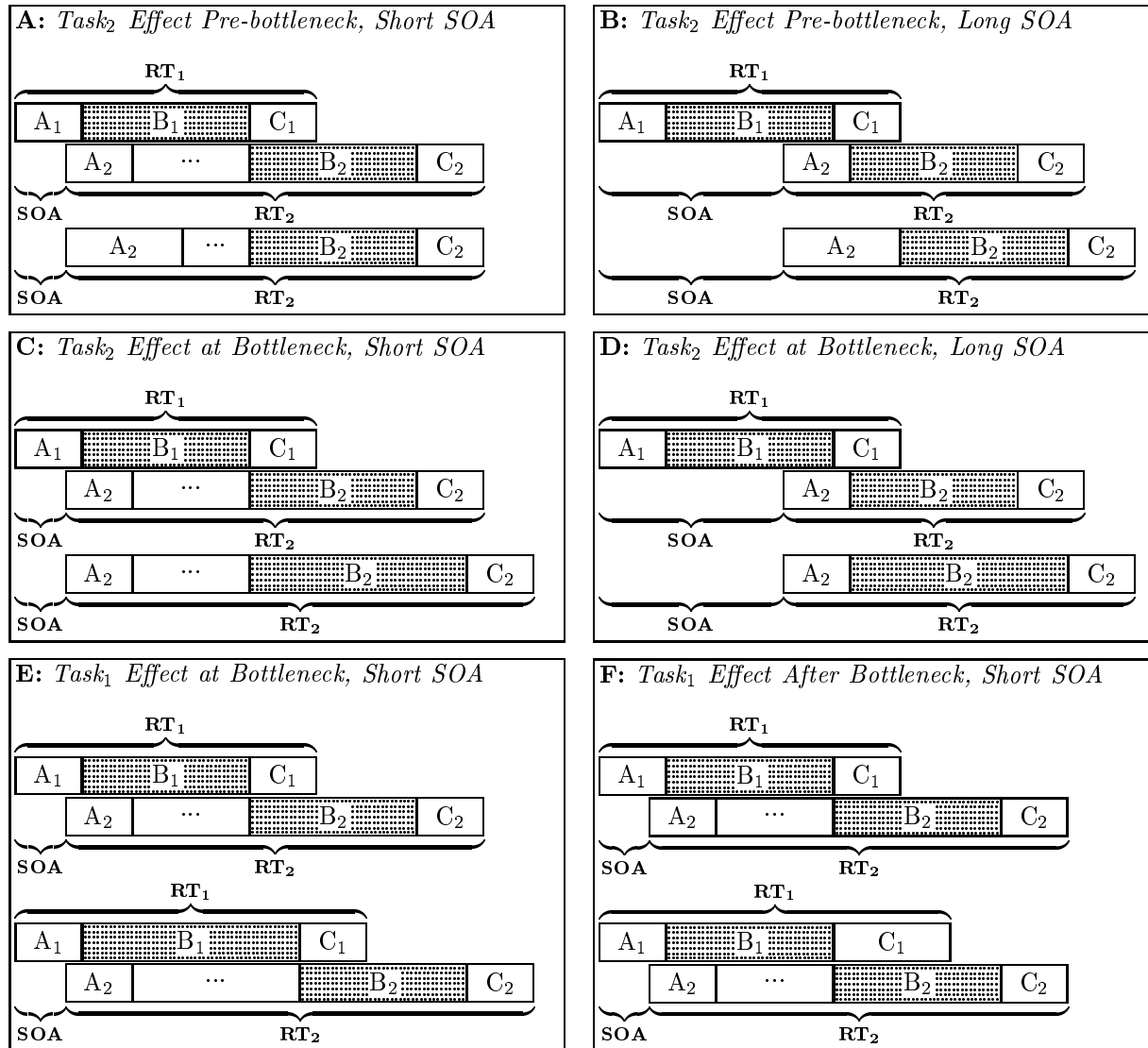When the SOA between T_1 and T_2 is short (Fig-

Figure Jolicœur.1. Stage diagrams showing the predicted task interactions in dual-task paradigms.

ure Jolicœur.1A) the pre-bottleneck processing in $Task_2$ can proceed without interference. This is illustrated by A_2 in Figure Jolicœur.1A. When pre-bottleneck processing is completed, the processing of T_2 is ready to engage the mechanisms that constitute the processing bottleneck. But they are busy with $Task_1$. The result is a period of waiting, represented by three dots, during which no further processing of T_2 takes place. When $Task_1$ no longer requires the bottleneck, processing of T_2 resumes. The initiation of bottleneck processing in $Task_2$ (B_2) thus coincides with the termination of bottleneck processing in $Task_1$ (B_1). RT_2 is the sum of stage durations plus the period of waiting (slack).

Now, suppose that a factor manipulated in $Task_2$ increases the duration of a pre-bottleneck stage, as represented by an increase in the length of A_2. When the SOA is very short, as shown in Figure Jolicœur.1A, this reduces the period of waiting before the initiation of bottleneck processing, but has no effect on RT_2. The effect of the factor is said to have been absorbed into the period of slack.

At longer SOAs (panel B), changing the duration of pre-bottleneck processing has the expected effect of increasing RT_2. Thus, the effect of the factor should decrease as SOA is reduced. The resulting interaction is often called underadditive with decreasing SOA (or with

increasing task overlap).

If the factor manipulated in $Task_2$ affects the duration of the bottleneck stage, additive effects of the factor and SOA are expected. This is shown in Figure Jolicœur.1 panels C (short SOA) and D (long SOA). Although a period of waiting (slack) is created by the contention for the bottleneck at short SOA, the effects of the factor are not absorbed into slack because the factor affects a stage of processing that occurs after the period of waiting. The increased duration of processing through the bottleneck stage is fully, and equally, reflected in RT_2 at both short and long SOA. Additivity is also predicted if the factor affects the duration of processing after the bottleneck (not shown).

This analysis, developed by Pashler and Johnston (1989), can be used to interpret the effects of $Task_2$ factors on RT_2 in the PRP paradigm. If the factor effects are additive with SOA, the factor must be affecting a stage that is either in or after the bottleneck. If the factor effects decrease in magnitude as SOA is reduced, then the factor must be affecting the duration of a stage that is before the bottleneck. This analysis is sometimes called the "locus-of-slack" logic, and strong support for the method has been provided in numerous studies (e.g., Pashler & Johnston, 1989; McCann & Johnston, 1992; see Pashler, 1994a, for a review).

Figure Jolicœur.1E–F illustrates another prediction of the postponement model of the PRP effect, concerning a factor manipulated in $Task_1$. If the effect of the factor is to lengthen the duration of processing either at the bottleneck (Figure Jolicœur.1E), or before, then the effect should carry over to response times in $Task_2$ as well. The longer bottleneck duration in the bottom pair postpones the onset of processing at the bottleneck stage in $Task_2$, which results in a longer RT_2. At a very short SOA, as illustrated, the effect of the $Task_1$ factor should be the same on RT_1 and RT_2. Support for this prediction can be found in Smith (1967), Van Selst, Ruthruff, and Johnston (1998), Williams (1974), and Pashler, (1994b). In Figure Jolicœur.1F, a $Task_1$ factor affecting processing after the bottleneck is assumed. While this factor would affect RT_1, no effect should be observed on RT_2 (see Pashler, 1994b, for some supporting evidence). The conclusion, therefore, is that a factor manipulated in $Task_1$ whose effects carry over to RT_2 must affect a stage that is either in or before the bottleneck, but not after the bottleneck.

In general, effects of $Task_1$ variables on RT_2 such as the one in Figure Jolicœur.1E are expected only at short SOAs. At longer SOAs, response times in $Task_2$ are not predicted to be influenced by $Task_1$ variables because these effects are mediated by the contention for the bottleneck, and no such contention takes place if the SOA is long enough.

For the AB paradigm, we are concerned with the effects of factor manipulations in $Task_1$ on performance in $Task_2$. The analysis of factor effects shown in Figure Jolicœur.1E–F also applies to the AB paradigm, although predictions are now made for accuracy in $Task_2$, rather than for RT_2. In the AB paradigm, response times in $Task_2$ are not measured, instead the paradigm focuses on report accuracy to a masked target. For a wide range of possible models, including all extant models, a factor manipulated in $Task_1$ of an AB experiment is not expected to affect accuracy in $Task_2$ if the variable affects processing after the locus or loci of interference causing the AB effect. Therefore, if a $Task_1$ factor modulates the magnitude of the AB effect, which is measured as a change of accuracy in $Task_2$, the factor must be affecting a stage of processing that is either in or before the locus of AB interference (see Jolicœur, 1998a). Such effects are expected only at shorter SOAs; at longer SOAs, there is no contention for processing capacity and thus no expected dual-task interactions. Clearly, some caution is required here because it is not difficult to think of events that could occur after the critical task interactions causing the AB effect that could cause a significant loss of information about T_2. The argument is sound, however, as long as the deficits in $Task_2$ remain clearly time-locked to the occurence of T_1 at short SOAs with a recovery to baseline conditions at long SOAs, and as long as we remain within the boundary conditions of the paradigms usually used to study the AB phenomenon.

To account for the AB effect using postponement models, it must also be assumed that there is a loss of information about T_2 during the period of waiting, with greater loss for longer waits (Jolicœur, 1998a). The results of Jolicœur (1999a) and Giesbrecht and DiLollo (1998) suggest that such loss does not occur if T_2 is not masked, presumably because persistence provides a form of storage of the information that can bridge the period of waiting.

Locus of AB Interference Relative to the PRP Bottleneck

In this chapter, we present first a cross-modal AB experiment in which the first target was a pure tone and the second target was a visually-presented letter in an RSVP stream. The main factor manipulated in $Task_1$ was the number of stimulus and response alternatives. This manipulation had a large effect on the magnitude of the AB effect. The conclusion is that this factor must have its effect either in or before a locus of interference causing the AB phenomenon. In Experiment 2, the same manipulation was performed, but in $Task_2$ of a PRP experiment, and the effects were additive with with SOA. The conclusion is that this factor must have its effect(s) either in or after the PRP bottleneck. Together, these results lead to the conclusion that at least one locus of AB interference must be either in or after the PRP bottleneck.

Jolicœur.2 EXPERIMENT 1

Experiment 1 used a cross-modal speeded AB paradigm. T_1 was a pure tone and $Task_1$ was an immediate speeded choice response based on pitch. T_2 was a visual stimulus, the letter X or Y, presented on every trial, embedded within an RSVP stream. $Task_2$ was a deferred and unspeeded discrimination between X and Y (see also Jolicœur, 1998ab, 1999b). The tone was presented concurrently with one of the letters in the RSVP stream.

There were two versions of $Task_1$. One had two tone frequencies and two responses; the other had four frequencies and four responses. Based on earlier work, we hypothesized that the two-alternative $Task_1$ would be associated with a shorter period of central processing than the four-alternative $Task_1$ (Van Selst & Jolicœur, 1997; Schubert, 1999). According to Van Selst and Jolicœur (1997), this difference in processing should occur in or after the PRP bottleneck. This assumption is verified in Experiment 2.

Strong claims have been made regarding the outcome of experiments like this. Pashler (1993) has influentially claimed that a speeded task will not produce an SOA-dependent deficit on a closely-following unspeeded task. Duncan et al. (1994) have claimed that there is absolutely no crossmodal AB. Yet, earlier work in our laboratory has shown that a speeded response to a tone can cause a significant AB effect in a concurrent visual encoding $Task_2$ (Jolicœur, 1998b; Jolicœur & Dell'Acqua, 1998c). Experiment 1 repeated Jolicœur's (1998b) experiment but also including two levels of $Task_1$ difficulty designed to influence the duration of central processing.

Method

Subjects. Twenty-six undergraduates at the University of Waterloo participated for pay. All reported having normal or corrected-to-normal vision, and normal hearing.

Stimuli. The auditory stimuli were pure tones presented well-above threshold for 100 ms at a frequency of 200, 363, 660, or 1200 Hz, using the internal speaker in the computer. The middle two frequencies (363 and 660 Hz) were used in the two-alternative condition.

The visual stimuli were white upper-case letters on a black background presented in RSVP at the center of a computer screen (CRT), at a rate of 10 letters/s (100 ms each with no blank inter-stimulus interval).

Between 6 and 9 letters were presented prior to the letter concurrent with the tone, and 12 to 15 after the tone. The X or Y could occur at positions 1, 3, 5, 7, 9, or 11, following the tone, with equal probability. Thus, even the last target position had 1 to 4 letters following it, ensuring that T_2 was always effectively masked (Giesbrecht & Di Lollo, 1998; Jolicœur, 1999a).

On every trial, the background stream items were selected at random, without replacement, from the letters of the alphabet, excluding H, S, X, and Y. Each letter subtended about 1° of visual angle and had a luminance of about 25 cd/m^2 and CIE(x,y) coordinates of (.278, .306). The background was black with a luminance of less than 1 cd/m^2.

Procedure. Each trial began with two symbols at the center of the screen, which provided both fixation markers and performance feedback for the previous trial. A press of the space bar eliminated the fixation/feedback symbols and initiated the RSVP sequence. A tone (T_1) was presented on half of the trials. Trials with no tone served as control trials in which preparation was equivalent to that in experimental trials. Tone-present and tone-absent trials were intermixed at random within each test session.

The experiment was divided into two sessions separated by a short break. In one session $Task_1$ involved two choices (363 Hz → ">"; 660 Hz → "?"). In the other session, $Task_1$ involved four choices (200 Hz → "M"; 363 Hz → "<"; 660 Hz → ">" 1200 Hz → "?"). The response buttons were contiguous on the bottom right row of the keyboard, and responses were made with the index, middle, ring, and little fingers of the right hand. The index and middle fingers were used for the two-alternative $Task_1$. The instructions were to press the correct response button as quickly as possible after hearing the tone, while keeping errors to a minimum. A message asking the subject to respond more quickly to the tone was presented if the RT to the tone was greater than 1300 ms.

At the end of every trial, after the response to the tone, a prompt asked the subject to indicate which visual target had been shown (X or Y). The X key was used to respond 'X,' and the C key was used to respond 'Y.' This response was not speeded.

The two-alternative discrimination session consisted of one block of 48 practice trials, followed by 3 blocks of 96 trials. The four-alternative discrimination session consisted of two block of 48 practice trials, followed by 3 blocks of 96 trials. The order of sessions was counterbalanced across subjects.

Each block of experimental trials in the four-alternative $Task_1$ contained a full crossing of T_1–T_2 SOA (100, 300, 500, 700, 900, or 1100 ms), T_1 frequency, T_1 present versus absent, and T_2 identity (X versus Y). When T_1 was not presented, a corresponding position in the RSVP stream was selected nonetheless. This made it possible to create control trials in which the absolute position of T_2 in the RSVP stream was equated across T_1-present and T_1-absent trials. Each block of experimental trials in the two-alternative $Task_1$ contained two full crossings of the experimental variables. Different random orders of the trials were used for each block and for each subject. Performance feedback was given in the form of a plus or minus sign for each response, at fixation, following each trial.

Results

The data from three subjects were eliminated. Two had $Task_2$ less than 69% correct in the control condition in one or both sessions and one was correct on only 54% of four-alternative tone task trials. The analyses presented below are based on 13248 pairs of responses generated by the remaining 23 subjects.

Correct trials in tone-present trials were screened for outliers using a close variant of the Van Selst and Jolicœur (1994) procedure (e.g., Jolicœur, 1998ab, 1999ab). Less than 1.9% of the trials were rejected. Analyses based on data that included outliers produced the same patterns of results.

$Task_2$. Figure Jolicœur.2A displays mean accuracy in

$Task_2$. Both versions of $Task_1$ produced large AB effects. In an analysis of the two-alternative condition, the interaction between SOA and T_1 present/absent was highly significant, $F(5, 110) = 6.91$, $p < .0001$, as were the two main effects, $p < .0001$ in both cases. In a separate analysis of the four-alternative condition, the SOA by T_1 (present/absent) interaction was highly significant, $F(5, 110) = 10.94$, $p < .0001$, as were the two main effects, $p < .0001$ in both cases.
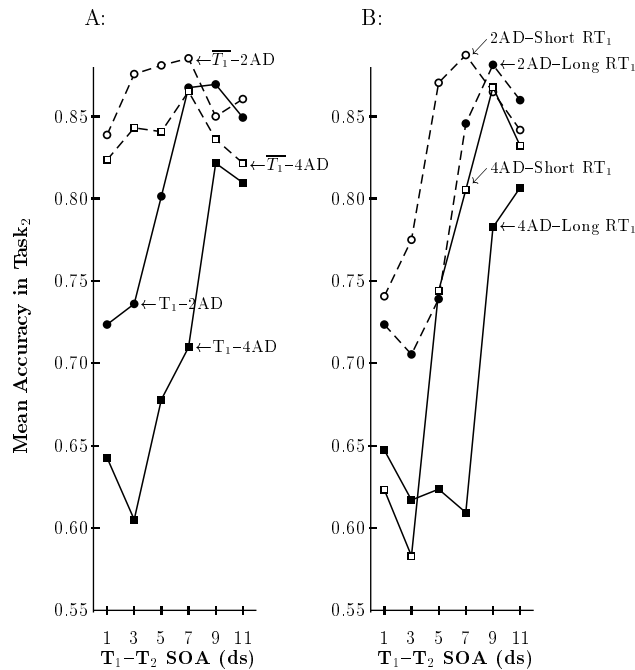

Figure Jolicœur.2. Mean proportion correct in $Task_2$ of Experiment 1. A: Results for each SOA, each level of $Task_1$ difficulty (two-alternatives: circular symbols; four-alternatives: square symbols), for trials on which T_1 was presented (filled symbols, solid lines), or omitted (unfilled symbols, dashed lines). B: Results for each SOA, each level of $Task_1$ difficulty (two-alternatives: circular symbols, dashed lines; four-alternatives: square symbols, solid lines), for trials in which T_1 was presented, depending on the duration of RT_1 (short RT_1 [below the median], open symbols; long RT_1 [above the median], filled symbols).

A separate analysis of the data from the T_1-present trials revealed a significant interaction between the number of $Task_1$ response alternatives and SOA, $F(5, 110) = 2.44$, $p < .04$. There was also a large main effect of number of $Task_1$ alternatives, $F(1, 22) = 43.53$, $p < .0001$, corroborating what can be seen in Figure Jolicœur.2, namely that accuracy in $Task_2$ was lower when $Task_1$ had four response alternatives than when it had only two. A companion analysis examining the control trials showed that the control conditions differed in overall levels of performance across the two and four-alternative versions of $Task_1$, $F(1, 22) = 9.47$, $p < .006$. However, there was no main effect of SOA and no interaction for the control conditions ($p > .05$ in both cases).

The three-way interaction between SOA, T_1 (present versus absent), and number of $Task_1$ responses was not significant in the omnibus ANOVA, but the interaction between number of $Task_1$ responses and T_1 (present versus absent) was highly significant, $F(1, 22) = 24.42$, $p < .0001$, reflecting the larger difference between the experimental and control conditions for the four-alternative than for the two-alternative $Task_1$ condition. The AB effect was reliably larger in the four-alternative condition than in the two-alternative condition.

We also compared the difference between control and experimental performance during the blink versus after the blink, as a more direct test of the difference in AB effects across conditions (this more sensitive test is justified by *a priori* expectations; see Jolicœur, 1998a). The difference between average control performance and the average of the the first four SOAs (during the blink) was contrasted with the difference between the control condition and the average of the last two SOAs (after the blink). This difference was significantly larger for the four-alternative condition than for the two-alternative condition, $F(1, 22) = 15.66$, $p < .0007$.

$Task_1$. As expected, mean RT_1 was longer for four alternatives (691 ms) than for two (530 ms), $F(1, 22) = 217.37$, $p < .0001$. Neither the main effect of SOA, $F(5, 110) = 1.55$, $p > .18$, nor the interaction between SOA and number of $Task_1$ alternatives, $F(5, 110) = 1.41$, $p > .22$, were significant.

$Task_1$ accuracy was higher for two alternatives (93.2%) than for four (77.4%), $F(1, 22) = 105.84$, $p < .0001$. There was no significant effect of SOA and no interaction between SOA and number of $Task_1$ alternatives ($p > .29$ in both cases).

$Task_2$ as a Function of RT_1. Accuracy in $Task_2$ was also examined, as a function of the speed of processing in $Task_1$. The trials on which T_1 was presented were divided into cells for each subject, each SOA, whether $Task_1$ had two or four alternatives, and for each of the three blocks of trials within each session. For each of these cells, the trials were sorted further into two more cells depending on whether RT_1 was above or below the median RT_1 in that bin. (Mean RT_1 was 456 ms for faster two-alternative responses, 596 ms for slower two-alternative responses, 606 ms for faster four-alternative responses, and 792 ms for slower four-alternative responses.) For each resulting cell, the mean accuracy in $Task_2$ was computed and submitted to an ANOVA with SOA, number of $Task_1$ alternatives, block, and RT_1-short/long as within-subjects factors. The means are displayed in Figure Jolicœur.2B

Accuracy in $Task_2$ was higher (.786) when RT_1 was shorter than the median and lower (.737) when RT_1 was longer than the median, $F(1, 22) = 23.09$, $p < .0001$. The interaction between RT_1-short/long and SOA was significant, $F(5, 110) = 5.03$, $p < .0003$, and this effect was modulated by the number of response alternatives, $F(5, 110) = 2.78$, $p < .025$, as shown in Figure Jolicœur.2B. The interaction between SOA and RT_1

appears to have the following form: Accuracy in $Task_2$ is similar across short and long RT_1s at very short SOAs, accuracy for short and long RT_1s diverge for intermediate SOAs, with lower accuracy for long RT_1s, followed by a convergence of accuracy levels across short and long RT_1s at the longest SOAs.

The main effect of block was significant, with accuracy remaining about the same from block 1 (.756) to block 2 (.745), and then improving in block 3 (.784), $F(2, 44) = 3.61$, $p < .0355$. The observed relationship between RT_1 and accuracy in $Task_2$ was not an artifact of a general improvement in performance in both tasks, as subjects became more practiced, because lower accuracy in $Task_2$ (for trials with a longer RT_1) was observed within each block or trials and because there was no overall increase in accuracy across blocks 1 and 2.

There was also little change in response times across blocks. Mean RT_1 was 619 ms in block 1, 613 ms in block 2, and 605 ms in block 3, and these means were not significantly different, $F(2, 44) = 1.56$, $p > .22$. Thus, it is unlikely that the association between RT_1 and accuracy in $Task_2$ could be due to correlated changes in overall performance levels with practice.

Discussion

The results were clear-cut: A larger AB effect was produced when $Task_1$ involved four alternatives rather than two alternatives (Figure Jolicœur.2). Furthermore, within each $Task_1$ condition, a larger and longer AB effect was found when processing of T_1 took longer. Both of these results support the hypothesis that a longer period of processing in $Task_1$ in one or more stages of processing carried over into accuracy scores in $Task_2$.

Jolicœur.3　EXPERIMENT 2

The interpretation of the results of Experiment 1 hinges critically on the locus of effect of the number of alternatives in $Task_1$. On the one hand, Van Selst and Jolicœur (1997) and Schubert (1999) both provided evidence that the locus is in or after the PRP bottleneck. They found that number of alternatives (two or more), when manipulated in $Task_2$ of a PRP experiment, produced additive effects with SOA. On the other hand, Schumacher, Lauber, Glass, Zurbriggen, Gmeindl, Kieras, and Meyer (1999) showed that underadditive interactions of number of alternatives and SOA can be found under certain conditions. The conditions used in $Task_1$ of Experiment 1 do not match exactly the conditions of any of these previous experiments, making it difficult to extrapolate from earlier work.

In Experiment 2, the manipulation used in $Task_1$ of Experiment 1 was applied in $Task_2$ of a PRP experiment. According to the locus-of-slack logic outlined earlier (Figure Jolicœur.1), if the manipulation used in Experiment 1 is at the stage of processing that causes PRP interference, or later, then additive effects of this variable should be observed with SOA. If some or all of the effect is at an earlier stage, then an underadditive interaction with SOA would result, as SOA is reduced.

Method

Subjects. The subjects were 33 undergraduates at the University of Waterloo who were paid volunteers. All reported having normal or corrected-to-normal vision, and normal hearing.

Stimuli. The auditory stimuli were identical to those used in Experiment 1. The visual stimuli were three letters, H, O, and S, presented at the same size and luminance as the stream items in Experiment 1. The exposure duration of the letter was 100 ms. The letter was not masked.

Procedure. Pressing the space bar removed the fixation symbols and initiated the trial sequence. After a delay of 750 ms, a letter was presented, requiring a speeded three-alternative choice response to be made with the left hand: H → ring finger ("Z" key); O → middle finger ("X" key); S → index finger ("C" key). The key mapping was described on a piece of paper that was at the top of the keyboard to facilitate learning during the practice trials.

After an SOA of 50, 200, 500, or 1100 ms, chosen pseudorandomly at run time, the tone was presented. The frequencies and frequency-response mappings (right hand) were identical to those in Experiment 1.

Each subject was tested in two sessions separated by a short break, one for the two-alternative and one for the four-alternative version of $Task_2$, in counterbalanced order. Each session began with 48 practice trials, followed by 6 blocks of 48 trials. Each block contained one or two full crossings of the independent variables. The order of trials was randomized anew for each block. Feedback was given in the form of a plus or minus sign at fixation, for each response, following each trial.

Results

The data from 6 subjects were excluded because of accuracy less than 50% in one or more cells in one or both tone tasks. The remaining 27 subjects produced 15552 experimental response pairs. Prior to RT analyses, the correct trials were first screened for outliers using the same algorithm as in Experiment 1. Screening based on RT_1 resulted in a loss of 2.8% of the trials. The surviving trials were then screened for outliers on RT_2, eliminating an additional 2.2%. Analyses performed on the unscreened data produced the same patterns of results as those reported below.

$Task_2$. The most important results concern mean RT_2, as a function of SOA and number of $Task_2$ alternatives, as shown in Figure Jolicœur.3. The main effect of SOA was highly significant, $F(3, 78) = 248.96$, $p < .0001$, as was the main effect of number of $Task_2$ alternatives, $F(1, 26) = 157.99$, $p < .0001$. However, the interaction between these two factors was not significant, $F(3, 78) = .19, MS_E = 1698.24$, $p > .90$. The difference between the four-alternative condition and the two-alternative condition was 199 ms at 50 ms SOA,
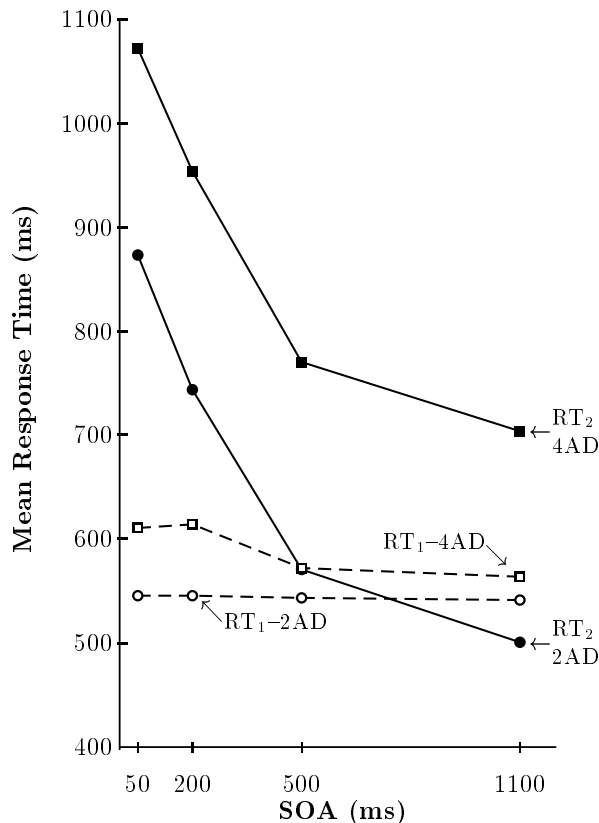
Figure Jolicœur.3. Results from Experiment 2. Mean response time in Task$_2$ (filled symbols, solid lines) and in Task$_1$ (open symbols, dashed lines), for each SOA, and each level of Task$_2$ difficulty (two-alternatives: circular symbols; four-alternatives: square symbols).

210 ms at 200 ms SOA, 200 ms at 500 ms SOA, and 203 ms at 1100 ms SOA.

Accuracy in Task$_2$ varied slightly as SOA increased (.845, .859, .874, and .866), $F(3, 78) = 5.22$, $p < .0024$. Accuracy was higher for two (.933) than for four alternatives (.789), $F(1, 26) = 160.65$, $p < .0001$. There was no interaction between these two variables, however, $F(3, 78) = .11, MS_E = .001483$, $p > .95$.

Task$_1$. The mean RT$_1$ for each SOA and each number of alternatives in Task$_2$ is also shown in Figure Jolicœur.3. The main effect of SOA was significant, $F(3, 78) = 7.94$, $p < .0001$, and mean RT$_1$ was also longer when there were four Task$_2$ alternatives (590 ms) than when there were two (544 ms), $F(1, 26) = 27.05$, $p < .0001$. These two variables also interacted, as shown in the figure, $F(3, 78) = 13.66$, $p < .0001$. The mean RT$_1$ was constant across SOAs for the two-alternative Task$_2$ condition, but it declined with increasing SOA for the four-alternative Task$_2$ condition. It is not clear to what these effects on RT$_1$ should be attributed, but their small magnitudes suggest that, in the main, the assumptions of the

postponement model of PRP were not badly violated.

Mean Task$_1$ accuracy was slightly higher when there were two alternatives in Task$_2$ (.962) than when there were four (.950), $F(1, 26) = 11.43$, $p < .0025$. Neither the main effect of SOA nor the interaction between SOA and number of Task$_2$ alternatives was significant ($p < 1$ in both cases).

Discussion

The results were clear-cut: The effects of varying the number of alternatives in Task$_2$ were additive with SOA. The implication is that this manipulation had an effect that was either in, or after, the PRP bottleneck. Given that the manipulation in Experiment 2 was identical to the one used in Task$_1$ of Experiment 1, it is reasonable to assume that effects of number of response alternatives in Experiment 1 also took place at or after the stage(s) of processing constituting the PRP bottleneck.

It was important to test directly whether the number of alternatives has its principal effect at or after the PRP bottleneck. A priori, one might have expected some of the effect to be relatively early, for example due to a greater difficulty of discrimination for four stimuli than for two stimuli. The frequencies were equally-spaced on a log scale (200, 363, 660, and 1200 Hz), in an attempt to produce approximately equal steps in perceived pitch, and the two tones used in the two-alternative condition were adjacent (363 and 660 Hz) in the sequence, in an attempt to equate the degree of perceptual difficulty across the two conditions. It appears that, under these conditions, the degree of perceptual difficulty in the two conditions was very similar, such that the main difference between them was later in processing, perhaps at response selection.

Jolicœur.4   GENERAL DISCUSSION

In Experiment 1, varying the number of stimulus-response alternatives in Task$_1$ of a speeded attentional blink paradigm produced a large modulation of the AB effect. Response times in Task$_1$ were clearly longer when there were more response alternatives in Task$_1$ than when there were fewer. Changes in the duration of the stage(s) of processing affected by this manipulation carried over into accuracy in Task$_2$. Therefore, the manipulation had its effects at, or prior to, the locus of dual-task interaction in the AB paradigm.

Experiment 2 showed that the manipulation of number of alternatives had its effect either in, or after, the PRP bottleneck, given that number of alternatives in Task$_2$ and SOA were additive in a PRP experiment (Figure Jolicœur.1, and Pashler & Johnston, 1989; Pashler, 1994a; McCann & Johnston, 1992).

Together, these two experiments lead to the conclusion that at least one locus of interference contributing to the AB phenomenon is either in or after the PRP bottleneck.

The results converge nicely with those of Jolicœur (1998ab; 1999ab) in suggesting a close connection between the dual-task interference observed in the AB

and PRP paradigms. In Experiment 1, large AB effects were obtained using stimuli presented in different sensory modalities, replicating and extending those of Jolicœur (1998b).

AB versus Task-switch Costs

Potter, Chun, Banks, and Muckenhoupt (1998) argued that there are two distinct attentional deficits in serial target search tasks, such as the one used in Experiment 1. One deficit, the attentional blink (AB) hypothesized by Raymond et al. (1992), was claimed to occur only when both target stimuli are visual, and not when one or both are auditory. The other deficit, an amodal effect, was hypothesized to be caused by capacity demands of task switching (as discussed in several other chapters in this volume).

If Potter et al. (1998) are correct, then one could argue that the observed deficits in $Task_2$ of Experiment 1 were due to task-switch costs, rather than to the within-modality AB effect studied by several researchers (e.g., Raymond et al., 1992; Ward et al., 1996). It could be that task-switch costs take place later in the system than the distinct within-modality AB effect postulated by Potter et al. (1998). If so, the evidence provided in Experiments 1–2 may apply only to the amodal AB effect, and not to the within-modality AB effect.

The present results suggests that at least some component of the AB effect occurs relatively late in the information processing stream (i.e., at or after the PRP bottleneck). Additional research will be required to determine whether our results apply to the within-modality AB effect, to the postulated amodal effect, or to both.

AB and Short-term Consolidation

Jolicœur and Dell'Acqua (1998a) showed that encoding information into memory causes responses in a subsequent speeded task to be delayed. In their Experiment 7, every trial began with the presentation of one or three letters exposed for 250 ms and followed by a pattern mask (100 ms). On "encode" trials, the letters had to be reported, without speed pressure, at the end of the trial. On "ignore" trials, the letters could be ignored. On every trial, the second stimulus was a tone to which the subjects made a speeded pitch-discrimination response (two-alternatives). The SOA between the letter display and the tone was varied between 350 ms to 1600 ms.

The response times to the tones are shown in Figure Jolicœur.4 (solid lines, filled symbols). Responses to the tone were delayed as the SOA between the letters and the tone was reduced, but only when the information had to be encoded (top two functions). Minimal effects of SOA were found when the the letters could be ignored (bottom function). A larger effect of SOA was found when more information had to be subjected to short-term consolidation (Encode-3) than when less information had to be encoded (Encode-1).

The results of Jolicœur and Dell'Acqua did not constrain the nature of the interference causing the delay in responses to the tone (i.e., postponement versus capacity-sharing). Computer simulations, however,
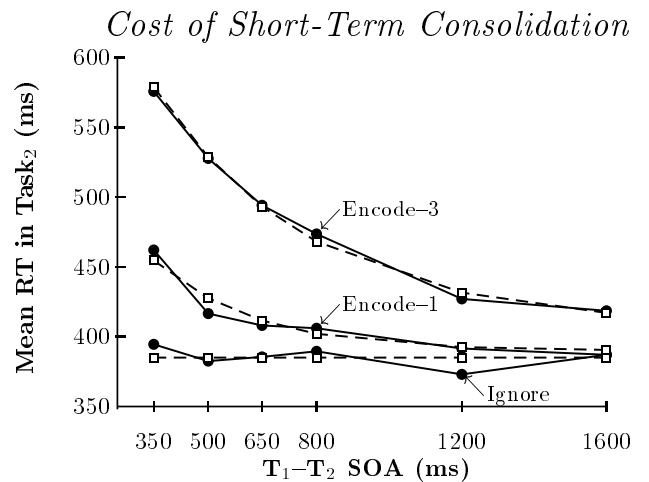

Figure Jolicœur.4. Results from Experiment 7 of Jolicœur and Dell'Acqua (1999a). Mean response time (RT_2) to the tone (in milliseconds) for each SOA, by whether the visual information was encoded (top two functions) or ignored (bottom function). The results from the encode condition are further split depending on the number of letters to be encoded (1, middle function, or 3, top function). The unfilled symbols joined by dottes lines show the results of a simulation in which it was assumed that response selection in the tone task was postponed for some period of time while the short-term consolidation of the information to be remembered was taking place.

showed that the results could be approximated reasonably well by assuming that some stage of processing in the tone task (e.g., response selection) was postponed for some time while short-term consolidation of the letters was taking place (see Figure Jolicœur.4 and Jolicœur & Dell'Acqua, 1998a). These results support the view that the short-term consolidation of information into a durable form of memory is a capacity-demanding operation that can delay or slow down other cognitive processes. Chun and Potter (1995) and Jolicœur (1998a; Jolicœur & Dell'Acqua, 1998ac; Crebolder & Jolicœur, 1999) argue that short-term consolidation is a likely locus of the dual-task interference causing the AB phenomenon.

Summary, Conclusions, and Implications for Control

In this chapter we have presented two new experiments designed to provide constraints on possible loci of interference contributing to the AB phenomenon. Experiment 1 showed that a large AB effect in an RSVP scanning task with a deferred response can be caused by performing a speeded response to a pure tone (see also Crebolder & Jolicœur, 1999; Jolicœur, 1998ab, 1999a; Jolicœur & Dell'Acqua, 1998b). Furthermore, larger effects resulted when the tone task had more stimulus-response alternatives. Also, within each version of $Task_1$, a larger AB effect was found when RT_1 was longer. The manipulation of $Task_1$ difficulty carried

over strongly onto $Task_2$, as expected if the manipulation in $Task_1$ was either in or before a locus of interference involved in the AB phenomenon.

In Experiment 2, the number of stimulus-response alternatives used in Experiment 1 ($Task_1$) was now used in $Task_2$ of a PRP experiment, and the effects were additive with SOA. Thus, the manipulation had its effects either in or after the PRP bottleneck. Consequently, at least one locus of interference causing the AB effect must be either in or after the PRP bottleneck.

Crebolder and Jolicœur (1999) performed a series of experiments that had the same logical structure as those in this chapter. Rather than manipulating number of alternatives in $Task_1$, they varied the relative frequency of T_1 in AB experiments and of T_2 in PRP experiments. In the AB experiments, T_1 and T_2 were both letters, and less frequent T_1 signals caused larger AB effects. Hence, the $Task_1$ manipulation carried over onto $Task_2$. These effects were found both when $Task_1$ was speeded and when $Task_1$ was unspeeded. Furthermore, effets of the frequency of T_2 were additive with SOA in PRP experiments. These results show that the conclusions based on Experiments 1–2 extend to within-modality AB paradigms, and to AB paradigms in which $Task_1$ is deferred.

The results suggest a closer connection between interference in the AB paradigm and in the PRP paradigm than has heretofore been supposed (e.g., Shapiro & Raymond, 1994; Chun & Potter, 1995; Ward et al., 1996). At least one major source of AB interference appears to be either at the same stage as the PRP bottleneck, or afterwards. While a locus after the PRP bottleneck is logically possible, this alternative seems less likely than loci of interference that coincide in the two paradigms. Of course, this contention needs to be put to further tests. Experiment 5 of Jolicœur, 1999a, however, already provides evidence against a very late locus involving motor codes.

Additional evidence for a similarity between AB interference and PRP interference was also reviewed. The results of Jolicœur and Dell'Acqua (1998ab) suggest that the short-term consolidation of visual information into memory causes responses in a concurrent tone task to be delayed, suggesting that short-term consolidation requires central capacity-limited mechanisms.

We began this chapter by noting that the issue of control has figured prominently in some recent theoretical work on the PRP phenomenon (Meyer & Kieras, 1997b), and of the AB phenomenon (Potter et al., 1998). Our results suggest that an effect at (or after) the PRP bottleneck also contributes substantially to the AB phenomenon. This effect, in the AB paradigm, could not be due to the need to control order of responses, because the second response in that paradigm is not speeded. Given that there is good evidence ruling out late (motor coding) accounts of the interference in such paradigms (e.g., Jolicœur, 1999a), the most natural explanation of AB effects in the Meyer-Kieras framework would be to suppose that interference takes place early, in mechanisms that operate prior to central processing. This type of

account, however, runs into difficulty given that a substantial component of the AB effect appears to be in or after the PRP bottleneck. A likely locus of effect for number of response alternatives (the main manipulation in Experiment 2) is response selection, and that locus is clearly beyond the early locus of interference that would be most easily incorporated into the Meyer-Kieras framework. This suggests to us that there may be more significant sources of structural central capacity limitations than are allowed for in the Meyer-Kieras framework (Meyer & Kieras, 1997). Indeed, the results suggest to us that structural central capacity limitations, rather than the need to control response order, may be contributing causes of both AB and PRP dual-task interference.

The consolidation of information into memory is one important process required to perform Task2 in the AB paradigm (Chun & Potter, 1995; Jolicœur, 1998a). The results of Jolicœur and Dell'Acqua (1998a) (e.g., Figure Jolicœur.4) strongly suggest that short-term consolidation of letters causes dual-task slowing in a concurrent cross-modal speeded task. Jolicœur and Dell'Acqua (1997) showed that encoding a random polygon also causes dual-task slowing. This latter result is important because random polygons do not have names in long-term memory, thus ruling out explanations that hinge on the use of names to represent stimuli. The results of Jolicœur and Dell'Acqua (1997, 1998a) show that dual-task slowing occurs even when only one response is speeded. This slowing, therefore, cannot be due to the need to control the order of output of two rapidly produced responses.

Although we argue that dual-task slowing in the Jolicœur and Dell'Acqua (1997, 1998a) experiments was not caused by consequences of strategic control, we want to highlight the important role of control for the results in that paradigm and in the AB paradigm. The key point is that short-term consolidation is not obligatory, but under active control. Indeed, in many AB experiments, the control condition consisted of trials in which a salient target was shown, but could be ignored (e.g., Raymond et al., 1992). These trials do not show the time-locked performance deficit that characterizes the AB effect. Similarly, "ignore" trials in the short-term consolidation experiments of Jolicœur and Dell'Acqua (1997, 1998a; Figure Jolicœur.4) do not exhibit the dual-task slowing found when the information has to be consolidated.

The selection of information to be consolidated and the onset of the consolidation process itself are both controlled operations. Given that short-term consolidation appears to involve a significant cost, in terms of the concomitant capacity demands, a key role for control processes is to minimize such costs by engaging capacity-demanding processes only when they are necessary.

Clearly, we are still quite far from having achieved a complete understanding of the AB and PRP phenomena. The present results and the evidence reviewed, however, suggest that a closer consideration of the similarities and differences between the patterns of interference in the

AB paradigm and in the PRP paradigm is likely to provide useful constraints on theorizing in both domains. This chapter was intended as a step in this direction.

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