EPISODIC BACKWARD RESPONSE COMPATIBILITY

DUAL TASK BACKWARD COMPATIBILITY EFFECTS ARE EPISODICALLY MEDIATED

BY MARIA GIAMMARCO, B.A. (Hons.)

A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree Master of Science

McMaster University MASTER OF SCIENCE (2012) Hamilton, Ontario (Psychology)

TITLE: Dual Task Backward Compatibility Effects are Episodically Mediated AUTHOR: Maria Giammarco, B.A. (Hons.), (McMaster University) SUPERVISOR: Dr. Scott Watter NUMBER OF PAGES: vi, 45

Abstract

Research on backward response compatibility effects (Task 2-to-Task 1 response priming) in the Psychological Refractory Period (PRP) paradigm has suggested that compatibility effects arise from episodic representations of Stimulus-Response (S-R) pairings (Hommel & Eglau, 2002). However, more recent work suggests that these effects are mediated by S-R rules held online in working memory during dual task performance (Ellenbogen & Meiran, 2008). We sought to dissociate these accounts. In Experiment 1, we observed the development of backward response compatibility effects over time in a common PRP task, following varying degrees of prior single task practice of the PRP component tasks. In Experiment 2, we trained participants on a PRP dual task, and then switched Task 2 to one of three different tasks with variable response mapping overlap with the original Task 2, before finally reverting back to the original PRP tasks. Backward response compatibility effects appeared initially, were abolished during the subsequent interference phase, and then reappeared with the original PRP task. Despite equivalent overall performance across conditions suggesting successful task rule instantiation in working memory to guide task performance, backward response compatibility effects were selectively absent in conditions where current S-R rules were mapped in conflict with prior S-R experiences within the experiment. Both experiments provide evidence in favour of an episodic account of backward response compatibility effects, in which prior learning influences subsequent performance in contextually relevant situations. Implications for the understanding of backward response compatibility mechanisms and parallel processing in the PRP paradigm are discussed.

Key Words: Psychological Refractory Period, dual task processing, backward response compatibility, divided attention, episodic memory, practice effects

Acknowledgments

I would like to thank my supervisor Scott Watter for his assistance and guidance through the completion of my Master of Science. I would also like to thank Sandra Thomson for her help and support throughout the past year. The completion of this thesis was a collaborative effort through the production of a joint publication (submitted to Attention, Perception, and Psychophysics) in which I produced a complete first draft later revised by Scott Watter and Sandra Thomson. Lastly I would like to thank Karin R. Humphreys, and members of McMaster University's Cognitive Science Laboratory (Esther Manoian, Mohammed Shariq Wani, Monika Polakowska, Claire Howarth, Rachel Den Boer, Stefania Cerisano, Sudhir Karthikeyan, and Tim Li) for useful discussion and assistance with data collection. This research was supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Grant #327454 to S.W. and by an NSERC post-graduate scholarship (PGS-D) to S.J.T.

Table of Contents

List of Figures and Tables

INTRODUCTION

It is well established that performance on a given task is impaired when it is performed concurrently with a second task, compared to when it is performed on its own (Pashler, 1994; Telford, 1931; Welford, 1952). This dual task interference is typically thought to be the result of a serial central bottleneck that prevents the processing of both tasks from occurring at the same time (Pashler, 1994; Welford, 1952). The Psychological Refractory Period (PRP) paradigm is a useful method for studying this bottleneck in performance. Here, the stimuli for two tasks are presented, separated in time by a variable stimulus onset asynchrony (SOA), and response times for both tasks are evaluated. Task 1 is relatively unaffected by SOA, as task instructions typically emphasize completing this task first, but Task 2 is particularly sensitive to SOA. When Task 1 and Task 2 overlap at short SOAs, responses to Task 2 are slower than when there is no overlap at long SOAs. According to the bottleneck theory, the response selection stages of two tasks cannot overlap, and therefore the central processing of Task 2 must wait until the central processing of Task 1 is complete, resulting in delayed response times for Task 2.

The response selection bottleneck is often considered to be a structural processing limitation. Studies have demonstrated that dual task interference persists after substantial amounts of dual task training (Ruthruff, Johnston, & Van Selst, 2001; Tombu & Jolicoeur, 1994; Van Selst, Ruthruff, & Johnston, 1999), when participants are instructed to place equal emphasis on both tasks (Ruthruff, Pashler, & Hazeltine, 2003; Ruthruff, Pashler, & Klassen, 2001;), and even after strong incentives for parallel performance (Ruthruff, Johnston, & Remington, 2009). However, much work has also been done that challenges the serial bottleneck model (Ellenbogen & Meiran, 2008; Hommel, 1998; Logan, Miller, & Strayer, 2011; Miller, 2006; Miller & Alderton, 2006; Watter & Logan, 2006). Recent evidence seems to suggest that Task 1 processing is sensitive to the influence of response compatibility from Task 2 information, and that a certain degree of central parallel processing in dual task performance is possible. Figure 1 illustrates the classic serial and discrete central response selection bottleneck model, and a modified version suggesting one potential model of central parallel operation of response selection processes.

The first serious challenge to the serial bottleneck model comes from Hommel's (1998) work on compatibility effects in a visual-manual PRP paradigm. Hommel (1998) found that performance in Task 1 was faster if there was response compatibility between Task 1 and Task 2 or semantic compatibility between the Task 2 response and Task 1 stimulus, suggesting that some degree of central Task 2 processing occurs in parallel with central processing of Task 1. Hommel distinguished between response activation and response selection stages, suggesting it is response activation that contributes to parallel processing, while response selection remains serial and contributes to persisting patterns of dual task interference in Task 2 that are apparent alongside compatibility effects. Subsequent work by Watter and Logan (2006) dissociated compatibility effects on Task 1 from semantic- versus response-related information from Task 2, providing further evidence of parallel response selection that cannot be easily explained by the serial bottleneck model.

Little is known about the mechanism underlying the backward response compatibility effect. It is clear that response information must be generated for both tasks concurrently, but exactly how this information is derived, especially for the unattended Task 2, is not yet clear. Hommel (1998) suggested two potential models of automatic stimulus-response (S-R) translation in dual task performance: the transient-link model and the direct-link model. The transient-link model suggests that multiple S-R rules are held on-line in working memory and can facilitate automatic S-R translation for multiple tasks in parallel. Alternatively, the direct-link model suggests an episodic memory account in which learned S-R associations can bypass controlled working memory governed processes and allow for parallel response activation. According to the direct-link model, compatibility effects ought to become stronger with practice, as stimuli become associated with responses through experience, leading eventually to automatic episodic retrieval of response information without the need for explicit mapping of stimuli to responses via the task set rules. Hommel found that backward compatibility effects emerged after only a few trials and there was no reliable change in the magnitude of the effect with practice, indirectly lending support to the transient-link model.

In addition to automatic S-R translation, Thomson, Watter, & Finkelshtein (2010) demonstrated that more abstract category-level response information can be computed for two tasks in parallel. Whereas Hommel (1998), Watter and Logan (2006) and others used small sets of repeating stimuli, Thomson et al. in their Experiment 2 examined response compatibility effects in a situation where a unique Task 2 stimulus was presented on every trial. The response compatibility effect they demonstrated in Task 1 therefore could not be due simply to automatic S-R translation, but were the result of parallel category-to-response (C-R) translation. This automatic C-R translation itself could be mediated by way of episodic learning of C-R associations or by concurrently represented task set rules held in working memory. This is consistent with earlier work by Reynvoet, Caessens, and Brysbaert (2002), who demonstrated semantic mediation of S-R associations in single task priming.

In contrast to the transient-link model of S-R (or C-R) translation via concurrently held rules in working memory, Hommel and Eglau (2002) found that backward compatibility effects were not affected by increasing working memory load. Instead, they observed that these effects persisted even when participants were instructed to no longer perform the second task, and they disappeared when the response mapping for the second task was reversed. These findings suggest that compatibility effects are not directly in line with the S-R mapping rules currently held online in working memory, but instead follow from acquired and enduring S-R associations.

However, more recent work by Ellenbogen and Meiran (2008) suggests that holding C-R rules for both tasks active in working memory is responsible for compatibility effects. Using a traditional PRP paradigm, they manipulated working memory load in a replication of Hommel and Eglau (2002): low working memory load conditions included 2 primary task rules, and high working memory load conditions included 4 primary task rules, but they also included a higher working memory load condition with 6 primary task rules. Compatibility effects were observed in the low and high working memory loads (replicating the results of Hommel and Eglau, 2002), but disappeared in the higher working memory load condition. These results suggest that working memory, and thus a transient-link based model, does seem to have a reliable influence on compatibility effects. In their final experiment they manipulate the response mapping of the 6 stimuli used in the highest working memory load condition, either mapping these to 6 different response categories as before, or mapping three stimuli to each of two responses. They showed that the backward response compatibility effect re-emerged for the 6 stimuli, 2 category condition, providing converging evidence with Thomson et al. (2010) that the response compatibility effect on Task 1 from Task 2 information is mediated by Task 2 C-R associations.

Ellenbogen and Meiran (2008) also inspected their data for practice effects by comparing the magnitude of the compatibility effect in the first and last block of trials. They observed significant practice effect only in the low working memory load condition (2 stimuli, 2 responses) of each experiment. They concede that in addition to working memory mediated effects, responses in low load conditions may be retrieved episodically once direct S-R associations are learned. They argue that increased working memory load appears to disrupt this episodic retrieval. However, the mere presence of practice effects points to the need for further examination of the notion that holding S-R rules online in working memory may not be the primary or sole determinant of compatibility effects.

Work on task-switching costs (Allport & Wylie, 1999, 2000; Wylie & Allport, 2000; Waszak, Hommel, & Allport, 2002) in fact provides complementary evidence that the direct-link model is a more likely source of Task 2-to-Task 1 response compatibility effects in dual task performance. In addition to general performance slowing with a switch of task, task switch costs are observed to be larger for stimuli that were present in both the prior and subsequent tasks, suggesting a form of proactive interference across tasks. The fact that such effects can be observed to be stimulus-specific, not global, suggests that the possibility that the automatic or unintended use of S-R associations may not be primarily mediated via rules held online in working memory. That is, these kinds of compatibility effects cannot be based only on holding S-R rules active, or else task switch costs would be the same for all stimuli, regardless of whether they were presented previously or not. Instead, such work points towards a learning and episodic memory based account of these compatibility effects, in line with the assumptions of the direct-link model. Essentially, S-R (or C-R) associations are acquired in the original task, represented in long term memory, and lead to proactive interference after a task-switch to repeated stimuli with different response mappings. The presentation of repeated stimuli leads to the contextually-influenced retrieval of the stimulus and related information. For example, Hommel (2004) describes this general model in terms of event files; the particular stimulus activates a host of information previously encoded with it in episodic memory, including the original experimental context and response, which leads to proactive interference on the present trial.

The Present Study

The purpose of the present study was to investigate the basic principles of the development of backward response compatibility effects. Previous findings have argued for both working memory and episodic accounts over the other, as the underlying source of these effects. The most recent of these, Ellenbogen and Meiran (2008) argued for transient rules held in working memory, after extending the work of Hommel and Eglau (2002) to show that a sufficiently high working memory load does in fact disrupt the backward compatibility effect. The present paper sought to further test this working memory explanation by asking whether episodic-style interference effects could be observed on backward compatibility effects, where an active working memory account would predict relative immunity from such effects.

In Experiment 1 we examined the effect of practice on developing response compatibility effects. Specifically, we aimed to determine if differential amounts of prior single task practice with Task 1 and Task 2 of a PRP paradigm would lead to different levels of backward response compatibility. If working memory mediated S-R or C-R translation underlies the backward compatibility effect, then we would predict that the amount of practice with various single tasks should not make a difference; once the task set rules have been instantiated, compatibility effects should emerge. However if compatibility effects are mediated more by retrieval of learned associations, we would expect that practice with Task 2 (and perhaps also Task 1) of a PRP paradigm should result in larger compatibility effects.

In Experiment 2, we more directly examined the effect of varying types of proactive interference from prior task experience on backward compatibility effects in dual tasks, by interleaving performance on the same PRP dual task with PRP performance using alternative Task 2 tasks across three separate experimental groups. We examined whether backward compatibility effects developed in the initial PRP phase were abolished when introducing an alternative and interfering Task 2 task (in part, akin to Hommel and Eglau, 2002), and then whether backward compatibility effects were recovered when reverting to the original PRP dual task, or whether interference effects persisted. This design lets us compare changes across task designs with different combinations of Task 2 interference and potential prior S-R or C-R learning, to more directly assess working memory (transient-link) or episodic memory (direct-link) accounts of backward response priming in dual task performance.

EXPERIMENT 1

In Experiment 1, we compared the effect of four different kinds of single task practice on subsequent performance and backward response compatibility effects in a PRP dual task. Separate groups of participants initially performed single task practice with both Task 1 and Task 2 of the eventual PRP task (Experiment 1A), only Task 2 plus an unrelated filler task (Experiment 1B), only Task 1 plus an unrelated filler task (Experiment 1C), or two unrelated filler tasks (Experiment 1D). Following single task practice of their respective tasks, all groups performed a common dual task PRP experiment using Task 1 and Task 2 as defined above. Our primary measure of interest throughout the experiment was the backward response compatibility effect in Task 1 RT data. Based on locus of slack logic and prior data from similar designs (e.g., Watter & Logan, 2006; Thomson, Watter & Finkelshtein, 2010), we expect to observe this effect (if present) most robustly at the earliest SOAs (here 0 ms SOA), with maximal overlap of processing stages between tasks and hence the best opportunity for Task 2-to-Task 1 response priming to occur.

Method

Participants

One hundred and three participants (87 females, mean age = 18.6 years) were recruited from the McMaster University undergraduate population. They were all enrolled in psychology courses and received partial course credit for their participation. All participants had normal or corrected to normal visual acuity, and normal colour vision. Twenty-five participants participated in Experiment 1A, and 26 participated in each of 1B, 1C, and 1D.

Apparatus and Stimuli

Stimuli were presented either on a 19-inch ViewSonic Professional Series P95f+ CRT monitor controlled by a Dell Dimension 4600 computer or a 21.5 inch Samsung SyncMaster B2240 LCD monitor controlled by an HP Pro 3130 computer, using Presentation® software (www.neurobs.com). The stimuli were identical in physical size across the two monitors. Participants were seated approximately 60 cm from the computer monitor and their responses were collected using a standard keyboard, the mouse, or the thumb joystick of a gamepad, depending on the task being completed.

Four basic tasks were used. For the *shape* task (PRP Task 1), the stimuli were line drawings of a star, a diamond, a circle, and a pentagon, filled in white. The height and width of each shape was approximately 1.25 degrees of visual angle. For the *colour* task (PRP Task 2), the stimuli were filled squares presented in orange, yellow, blue, or purple, with height and width of 1.25 degrees of visual angle. The stimuli for the *case* task (one of two Filler tasks) were four letters from the English alphabet (A, E, G, and R), presented either in uppercase or lowercase

Helvetica font, scaled to approximately 1.25 degrees of visual angle. Finally, in the *size* task (the second Filler task), the stimuli were 8 five-letter nouns, four of which referred to items that were larger than the computer monitor (bench, stove, piano, canoe), and four that referred to items smaller than the computer monitor (cigar, pearl, badge, spoon), scaled to an approximate height of 1.25 degrees of visual angle. All stimuli other than colour patches were presented in white on a black background; colour patches were solid colour, not outlined in white, to emphasize the colour value and not the square shape of the colour patch.

Design

The design for Experiment 1 is summarized in Figure 2. All participants completed a variable single task phase followed by a common dual task phase. In the single task phase participants practiced two different single tasks, alternating between these two tasks twice in counterbalanced order before commencing the dual task phase. The tasks used in the single task phase consisted of some combination of the component tasks used in the dual task phase (Task 1, Task 2), and/or two filler tasks that were not encountered in the dual task phase. Participants in Experiment 1A practiced both tasks used in the dual task phase: Task 1 and Task 2 (shape task and colour task, respectively). Participants in Experiment 1B practiced Task 2 (*colour* task) and the *case* filler task. Participants in Experiment 1C practiced Task 1 (*shape* task) and the *case* filler task. Participants in Experiment 1D practiced two different filler tasks (*case* task and *size* task). The dual task phase incorporated the *shape* and *colour* tasks as Task 1 and Task 2 (respectively) of a typical Psychological Refractory Period paradigm.

For Task 1 and Task 2 in both the single- and dual task phases, responses were collected using the number pad of a standard keyboard. Responses to the filler tasks were made using either gamepad joystick movements (*case* task) or mouse movements (*size* task), in order to minimize response mapping overlap with the tasks used in the dual task phase.

Procedure

Single task. Participants in each experimental group (Experiment 1A, 1B, 1C and 1D) experienced two of the four different single tasks used in Experiment 1. In the *shape task*, participants performed a shape discrimination task, pressing one response key if the shape was either a star or a diamond, and a different response key if the shape was a circle or a pentagon. Trials began with a fixation display consisting of two white dashes in the center of the screen against a black background, flanking the position where the shape would appear. After 500 ms, the fixation display was replaced with the shape stimulus for 1000 ms, followed by a blank screen for 1500 ms, until the next trial began. Participants responded by pressing the ‘1’ or ‘2’ key on the number pad of a standard keyboard using the index or middle finger of the right hand. The response mapping was counterbalanced across participants. In the *colour task*, participants judged the colour of a filled square stimulus by pressing one response key if the colour was yellow or orange, and another if the colour was purple or blue. The trial sequence and response keys were identical to those in the shape task.

In the *case* task, participants judged whether the presented letter was in upper- or lowercase. On every trial a letter was displayed in white in the center of the screen, next to a red square ‘cursor’ (approximately 1 degree of visual angle) that moved with the joystick of a gamepad. The display also included a horizontal line presented 6.5 degrees of visual angle above and below the letter stimulus. Participants were instructed to move the joystick with their left thumb above the top line if the letter was uppercase, and to move it below the bottom line if it was lowercase. Participants then pushed a button on the gamepad with their right thumb to submit their response. The trial display remained on the screen until participants initiated a button press response with the joystick at the top or bottom of the screen; button presses with the joystick cursor in any other location did not end the trial. At the end of each trial participants were instructed to release the joystick, so that it was in a neutral (central) position for the beginning of the following trial.

In the *size* task, participants judged whether a noun word referred to an object that was larger or smaller than the computer monitor. On every trial a word was displayed in white on the center of the screen against a black background, with a white '+' symbol cursor immediately below it. Participants were instructed to use the mouse to move the cursor as far left on the screen as possible if the word referred to something smaller than the monitor, and to move it to the right edge of the screen if the word referred to something larger than the computer monitor. Once the mouse moved to the edge of the monitor, the selection was recorded and the trial ended.

Each of the four blocks in the single task phase consisted of 96 trials, divided into 3 mini-blocks of 32 trials each. All stimuli were presented an equal number of times within a block. At the end of each mini-block, participants' average RT and accuracy for the mini-block were displayed, and they had the opportunity to rest before initiating the beginning of the next mini-block. Each time a new task was introduced, participants were informed and reminded of the task rules and response mappings for that task.

Dual task. All participants completed an identical dual task phase, where Task 1 was the *shape* task and Task 2 was the *colour* task, presented in a Psychological Refractory Period dual task paradigm. Every trial began with a fixation display for 500 ms, consisting of two rows of two dashes in the center of the screen, flanking the locations where the shape and colour stimuli would appear. The onset of the Task 1 and Task 2 stimuli were separated in time by an SOA of 0, 200, or 800 ms. Both stimuli were then displayed together for 1000 ms, with the shape stimulus presented directly above the coloured square, followed by a blank screen for 2000 ms. Participants made separate responses to each task by pressing the '1' or '2' key on the number pad of a standard keyboard. Response mapping was counterbalanced across participants, and where applicable was consistent with response mappings in the single task phase. Participants were instructed to respond to both tasks as quickly and accurately as possible, but to place special emphasis on the shape task (Task 1) and to make their response to it first before considering the colour task. Participants were provided with a note attached to the bottom of the monitor reminding them of the response mapping for both tasks.

The dual task phase consisted of 16 practice trials that were not included in the analysis, and 192 experimental trials, made up of 4 iterations of the factorial combination of the four Task 1 (shape) stimuli, four Task 2 (colour) stimuli, and three SOAs. These trials were divided into 6 blocks of 32 trials each. At the end of each block participants received feedback about their overall accuracy and RT for Task 1 for that block, and had the opportunity to rest before initiating the start of the next block.

Data Analysis

Our analyses focused on data from the dual task phase. Participants' data were excluded from analysis if their overall accuracy was less than 70%. This resulted in the elimination of 6 participants' data, leaving 24 participants in Experiment 1A, 26 in 1B, 25 in 1C, and 22 in 1D Trials with response latencies of less than 200 ms on either Task 1 or Task 2, or greater than 2000 ms for Task 1 or 2500 ms for Task 2, were excluded from analysis. Mean reaction times for each condition were computed from the remaining trials where both Task 1 and Task 2 responses were correct. We evaluated the response compatibility between Task 1 and Task 2 across each SOA separately for each task, and submitted the mean Task 1 and Task 2 RTs to separate 2 (Task 1 practiced or not; Exp. 1A and 1C versus 1B and 1D) x 2 (Task 2 practiced or not, Exp. 1A and 1B versus 1C and 1D) x 3 (SOA; 0, 200, 800 ms) x 2 (Task 1 to Task 2 response compatibility; compatible versus incompatible) ANOVAs, with the two task practice factors as between subjects variables, and SOA and response compatibility as within subject variables. Error data were analyzed separately for each task. Trials with an incorrect response for Task 1, regardless of Task 2 accuracy, and trials with an incorrect response for Task 2 following correct Task 1 performance were submitted to the same ANOVA design used for RT analysis.

Results

Task 1 RT

Effects of SOA and response compatibility for correct mean Task 1 and Task 2 RTs are displayed in Figure 3, separated by between-subjects practice conditions (Experiments 1A, 1B, 1C and 1D). For Task 1 RT data, the omnibus ANOVA revealed a strong main effect of response compatibility, $F(1, 93) = 33.22$, $p < 0.001$, with faster mean RT for trials where correct Task 1 responses were compatible with subsequent correct Task 2 responses within a trial. A main effect of prior Task 1 practice was observed, with faster Task 1 RTs for participants who practiced this task in the earlier single task phase versus a filler task, $F(1, 93) = 10.40$, $p < 0.001$. A non-significant but marginal main effect of SOA was observed, $F(2, 186) = 2.37$, $p = 0.097$, suggesting that the typical expectation of equivalent Task 1 RTs across SOAs in a PRP paradigm may have been violated. Post-hoc ANOVAs on RT1 data for individual experiment groups revealed a significant effect of SOA in Experiment 1C, $F(2, 48) = 3.88$, $p < 0.05$, but not in the other three groups. Finally, the above effects in the omnibus ANOVA for RT1 were modified by a significant 4-way interaction between Task 1 practice, Task 2 practice, SOA and response compatibility, $F(2, 186) = 3.45$, $p < 0.05$. This interaction supports the expected finding of response compatibility effects more prominent at short SOAs, and the observation of this maximal early SOA response compatibility effect primarily in Experiment 1A (both Task 1 and Task 2 practice) and Experiment 1D (no Task 1 or Task 2 practice).

Considering that we observed the predicted Task 2-to-Task 1 response compatibility effects on Task 1 RT at short SOAs most strongly in Experiment 1A and 1D, and that these two conditions offer the most direct contrast of the effect of practice on both tasks while controlling for dual task experience, we split each of these datasets into temporal halves to examine the time course of the development of response compatibility effects on RT1. Figure 4 shows response compatibility by SOA Task 1 RT data from these two experiment groups, divided by first versus second half of the dual task PRP phase. Given our a priori assumptions about where we should expect the most convincing evidence of Task 2 response information influencing Task 1 performance, our primary question was whether the response compatibility effect at the 0 ms SOA was consistent across time, or whether this effect might be initially absent but develop over time. For Experiment 1A data, where participants had practiced both Task 1 and Task 2 separately prior to PRP performance, the response compatibility effect at 0 ms SOA was substantial in both the first half, $t(24) = 5.13$, $p < 0.001$, and the second half, $t(24) = 3.53$, $p < 0.01$, of these data. In contrast, for Experiment 1D, where participants practiced neither Task 1 nor Task 2 prior to PRP performance, but instead practiced two unrelated filler tasks, the response compatibility effect at 0 ms SOA was not observed in the first half of the PRP task, $t(21) = 0.55$, $p = 0.59$, but was present in the second half, $t(21) = 3.47$, $p < 0.01$.

Task 2 RT

For Task 2 RT data, shown in Figure 3, the omnibus ANOVA revealed a strong main effect of SOA, $F(2, 186) = 1610.87$, $p < 0.001$, as expected within a PRP paradigm. Main effects of prior single task Task 1 practice, $F(1, 93) = 8.24$, $p < 0.01$, and Task 2 practice, $F(1, 93) = 4.98$, $p < 0.05$, were also observed, with faster Task 2 RTs for participants who practiced Task 1 and/or Task 2 in the earlier single task phase versus filler tasks. Prior single task practice on Task 1 and Task 2 appeared to be generally additive on overall dual task PRP Task 2 performance, with no interaction between Task 1 practice and Task 2 practice factors, $F(1, 93) = 1.55$, $p = 0.22$. However, separate interactions between SOA and Task 1 practice, $F(2, 186) = 3.24$, $p < 0.05$, and SOA and Task 2 practice, $F(2, 186) = 8.35$, $p < 0.001$, suggested independent effects of prior Task 1 or Task 2 practice on Task 2 RT, most obvious as greater speeding of Task 2 RT at short versus long SOA with prior task practice. Finally, SOA interacted with response compatibility, $F(2, 186) = 10.87$, $p < 0.001$, with compatible trials faster than incompatible trials more evident at shorter SOAs, modifying a marginal main effect of response compatibility, $F(1, 93) = 3.73$, $p = 0.057$. In addition, the marginal interaction of response compatibility, Task 1 practice and Task 2 practice, $F(1, 93) = 3.58$, $p = 0.062$, and the marginal interaction of SOA with these three factors, $F(2, 186) = 2.82$, $p = 0.061$, were observed, suggesting response compatibility effects at short SOA primarily in Experiment 1A (both Task 1 and Task 2 practice) and Experiment 1D (no Task 1 or Task 2 practice), mirroring effects in Task 1 RT. Post-hoc ANOVA on RT2 data for individual experiment groups revealed strong interactions of response compatibility with SOA in Experiment 1A, $F(2, 46) = 10.64$, $p < 0.001$, and Experiment 1D, $F(2, 42) = 6.23$, $p < 0.01$, but not in Experiment 1B or 1C.

Errors

Mean error rate data for Task 1 and Task 2 are summarized in Table 1. Given our focus on response compatibility effects in reaction time data in the present paper, for the sake of brevity we present a basic reporting and analysis of error data, beyond testing our critical Task 1 response compatibility data for potential speed-accuracy trade-off effects. Overall, the substantial majority of errors were committed on Task 2. In Task 1, we observed a strong response compatibility effect, $F(1,93) = 29.66$, $p < 0.001$, with fewer errors on response compatible versus incompatible trials, mirroring the RT findings and showing no evidence of a speed-accuracy trade-off in Task 1. Errors were most frequent at 0 ms SOA, and decreased as SOA increased, $F(2, 186) = 28.09$, $p < 0.001$. SOA and response compatibility interacted, with largest response compatibility differences at 0 ms SOA, reducing to small or non-existent differences at 800 ms SOA, $F(2, 186) = 9.74$, $p < 0.001$. For Task 2 error data, a strong reverse response compatibility was observed, $F(1, 93) = 68.92$, $p < 0.001$, with response compatible trials more errorful than incompatible trials across all conditions. A main effect of SOA reflected reduced errors as SOA increased, $F(2, 186) = 5.90$, $p < 0.01$, akin to the effect of SOA on errors in Task 1.

Discussion

In Experiment 1 we sought to test the effects of prior single task practice on response compatibility effects in dual task performance. Response compatibility effects on Task 1 from Task 2 (see Figure 3) were observed most strongly when both Task 1 and Task 2 were practiced as single tasks prior to dual task PRP performance (Experiment 1A), compared to conditions where only Task 2 (Experiment 1B) or Task 1 (Experiment 1C) were practiced along with filler tasks prior to the common PRP dual task. While PRP performance in Experiment 1D (no prior single task practice with either Task 1 or Task 2) was slowest across all groups, a sizable response compatibility effect was observed in this group.

A comparison of demonstrated Task 1 response compatibility effects between Experiments 1A and 1D allowed us to make the most direct assessment of the development of this effect over practice, equating for dual task experience between groups (see Figure 4). Assessment of first versus second half data showed robust early SOA response compatibility effects in both halves of the PRP task following prior single task practice of Task 1 and Task 2 (Experiment 1A). In contrast, with no prior single task practice, a response compatibility effect was minimal in the first half of Experiment 1D PRP performance, but was evident only in the second half of these data.

We suggest that these findings argue in favour of an episodic memory account of S-R (or C-R) mediated backward response compatibility effects (following Hommel, 1998, a direct-link model), over an account involving the active representation of these S-R (or C-R) rules in working memory (a transient-link account). Our data show clear effects of prior task practice with specific tasks influencing subsequent PRP performance. Importantly, we also demonstrate the relative absence of backward response compatibility effects in situations with little or no prior experience with component PRP tasks. Given that participants could successfully perform the PRP dual task with reasonable RT and accuracy across all conditions, we assume that task rules were sufficiently instantiated during trials to control task performance. In this situation, a working memory-mediated transient link model should predict backward compatibility effects in all cases, in contrast to our observed data.

Interestingly, response compatibility effects on Task 2 RT data closely mirrored effects in Task 1 RT. Considering that responses on both tasks in a given PRP trial must be both response compatible or both incompatible, the close relationship of Task 1 and Task 2 response compatibility effects could suggest that Task 2 effects are simply locus of slack carryover effects reflecting primary differences in Task 1 RT. Despite these current data, findings from prior work (e.g., Watter and Logan, 2006; Thomson, Watter & Finkelshtein, 2010) have shown compatibility and priming effects on Task 2 from Task 1, in addition to these carryover effects from Task 1. In our current situation, close correspondence of response compatibility effects in Task 1 and Task 2 RT data might allow effects observed in Task 2 RT to add confidence to our observation of concordant response compatibility effects in corresponding Task 1 conditions.

EXPERIMENT 2

In Experiment 2, we sought to more directly compare the ability for potential working memory-mediated response compatibility effects to arise over changing S-R (or C-R) task rule conditions, versus the potential for episodic memory-mediated response compatibility effects to emerge relative to prior experience with specific S-R (or C-R) task rules. Three separate experimental groups were established, and all performed the same PRP dual task in an initial 9-block Before phase, and again in a final 3-block After phase of each experiment. This main PRP dual task asked participants to identify shapes as Task 1, and to judge single digits as numerically higher or lower than 5 as Task 2. Between Before and After phases, each experimental group performed a PRP task with a different Task 2 in a 3-block Interference phase: in Experiment 2A, participants judged the same digits as either odd or even (conflict T2 mapping); in Experiment 2B, participants performed the same numerical high/low task with the opposite Task 2 response mappings (reversed T2 mapping); and in Experiment 2C, participants identified colour patches (low-conflict T2 mapping).

Critically, we examined response compatibility effects on Task 1 in Before, Interference, and After phases, across the three different experiment groups. A working memory-mediated transient-link model would predict response compatibility effects in all conditions, so long as working memory load was not excessive and task performance was sufficient to assume that S-R (or C-R) rules were being held in working memory to allow adequate task performance. An episodic direct-link model would predict that potential backward response compatibility effects arising in the Before phase would be substantially interrupted in the Interference phase in Experiment 2A and 2B, with varying kinds of overlapping S-R and C-R rules, but perhaps not in Experiment 2C where new Task 2 rules have much less overlap. Finally, a direct-link model would predict the recovery of response compatibility effects in the After phase, given sufficient episodic learning established in the Before phase.

Method

Participants

Fifty-five participants (45 females, mean age = 18.8 years) were recruited from the McMaster University undergraduate population. They were all enrolled in psychology courses and received partial course credit for their participation. All participants had normal or corrected to normal visual acuity, and normal colour vision. Seventeen participants participated in each of Experiment 2A and 2B, and 21 participated in 2C.

Apparatus and Stimuli

All stimuli were presented on a 19-inch ViewSonic Professional Series P95f+ CRT monitor controlled by a Dell Dimension 4600 computer using Presentation® software (www.neurobs.com). Participants were seated approximately 60 cm from the computer monitor and their responses were collected using a standard keyboard.

Three basic tasks were used. Stimuli for the *shape* task (Task 1 in all phases of each experimental condition), and the *colour* task (Task 2 in the interference condition of experiment

2C) were identical to those used for these same tasks in Experiment 1. For both the *high/low* task (Task 2 in the Before and After phases and in the Interference condition for experiment 2B) and the *odd/even* task (Task 2 in the interference condition for 2A), the stimuli were the digits 1 to 9 excluding 5, presented in white against a black background, with a height of 1.25 degrees of visual angle.

Design

All participants completed three typical PRP dual task phases. All participants performed the shape task as Task 1 throughout the experiment. Task 2 in the Before and After phases was always the high/low task. Task 2 in the intervening Interference phase differed across the three experimental conditions: Participants in Experiment 2A performed an odd/even number judgment (Task 2 conflict mapping), participants in Experiment 2B performed a high/low number judgement with response mapping reversed compared to Before and After phases (Task 2 reversed mapping), and participants in Experiment 2C performed a colour task (Task 2 low-conflict mapping).

Procedure

The trial sequence for all three phases was identical to the dual task phase of Experiment 1, except for the specific Task 2 stimuli presented. The Before phase consisted of 16 practice trials that were not included in the analysis, and 288 experimental trials, made up of three iterations of the factorial combination of the 4 Task 1 shape stimuli, the 8 Task 2 digit stimuli, and the 3 SOAs. These trials were divided into 9 mini-blocks of 32 trials each. Response mapping was counterbalanced across participants and participants were again provided with a note attached to the bottom of the monitor reminding them of the response mapping for both tasks. The After phase was identical to the Before phase but consisted of 96 experimental trials, made up of a single iteration of the factorial combination of stimuli and SOAs, and divided into three mini-blocks.

At the beginning of the Interference phase, participants were given instructions about the new task they would perform as Task 2 and/or the new response mapping for this task. For Experiment 2A (conflict mapping), the Task 2 stimuli remained the same as in the Before phase, but participants were now instructed to perform odd/even judgments for each digit. Under these new task rules, half of the stimuli were associated with the same response as in the Before phase, and half were assigned the opposite response. For Experiment 2B (reversed mapping), Task 2 remained consistent but the response mapping was reversed, and therefore all stimuli from the Before phase were now mapped to the opposite response. For Experiment 2C (low conflict mapping), participants were instructed to perform a novel Task 2 (colour task), with a new set of stimuli mapped to the same response keys from the Before phase. The Interference phase was the same length as the After phase, with 96 trials divided into three mini-blocks. As in Experiment 1, at the end of each mini-block in all phases participants were given feedback about their overall accuracy and average response time for Task 1 for the mini-block, and had the opportunity to rest before initiating the start of the next block.

Data Analysis

Participants' data were excluded from analysis if their overall accuracy was less than 70%. This resulted in the elimination of 7 participants' data, leaving 16 participants in each condition. Trials with response latencies of less than 200 ms on either Task 1 or Task 2, or greater than 2000 ms for Task 1 or 2500 ms for Task 2, were excluded from analysis. Mean reaction times were computed for the remaining trials where both Task 1 and Task 2 responses were correct. We evaluated the response compatibility between Task 1 and Task 2 across each

SOA separately for each task, and submitted the mean Task 1 and Task 2 RTs to separate 3 (experimental group; Exp 2A, 2B, 2C) x 3 (experiment phase; Before, Interference, After) x 3 (SOA; 0, 200, 800) x 2 (Task 1 to Task 2 response compatibility; compatible or incompatible) ANOVAs, with experimental group as a between subjects variable and all other variables as within subjects. ANOVAs were followed by directed post-hoc analyses focused on assessing the presence of backward compatibility effects across conditions.

Error data were analyzed separately for each task. Trials with an incorrect response for Task 1, regardless of Task 2 accuracy, and trials with an incorrect response for Task 2 following correct Task 1 performance were submitted to the same analyses as RT data.

Results

Task 1 RT

Mean RT data for correct Task 1 and Task 2 trials for Experiment 2 are shown in Figure 5. Data within single panels display SOA and response compatibility data for Task 1 and Task 2, and are presented separately for Before, Interference and After phases, for each of Experiment 2A (conflict Task 2 mapping), Experiment 2B (reversed Task 2 mapping), and Experiment 2C (unrelated Task 2). For Task 1 RT data, the omnibus ANOVA revealed main effects of experiment phase, $F(2, 90) = 5.68$, $p < 0.01$, SOA, $F(2, 90) = 21.48$, $p < 0.001$, and response compatibility, $F(1, 45) = 38.45$, $p < 0.001$. These main effects were modified by interactions of experiment phase and SOA, $F(4, 180) = 6.35$, $p < 0.001$, experiment phase and response compatibility, $F(2, 90) = 3.71$, $p < 0.05$, and SOA by response compatibility, $F(2, 90) = 6.06$, $p < 0.01$, and the 3-way interaction of these factors, $F(4, 180) = 3.45$, $p < 0.01$. The effect of experiment group was observed via interactions of this factor with SOA, $F(4, 90) = 2.91$, $p < 0.05$, and with SOA and experiment phase, $F(8, 180) = 2.22$, $p < 0.05$.

This pattern of interactions supported the observation of response compatibility effects present in Task 1 data, most strongly at 0 ms SOA, with these effects present across all three experiment groups in Before and After phases, but generally absent in the Interference phase. The effect of SOA on Task 1 RT appeared to be minimal in the Before phase, and to develop and persist in Interference and After phases. To confirm and examine the above observations of response compatibility effects, we conducted a number of directed post-hoc analyses, as follows. We report here only the critical distinguishing effects not already evident from the omnibus ANOVA above.

First, we repeated our initial ANOVA considering only Before and Interference phases. We observed an interaction of experiment phase and response compatibility, $F(1, 45) = 6.14$, $p < 0.05$. There were no interactions involving response compatibility and experimental group, Fs < 1.5. Assessing just the Before phase data, we observed the main effect of response compatibility, $F(1, 45) = 38.79$, $p < 0.001$, and the interaction of SOA and response compatibility, $F(2,90) = 5.62$, $p < 0.01$, with the absence of any effects or interactions of experiment group, Fs < 1.1. Assessing just the Interference data, we observed no main effect of response compatibility, $F(1, 45) = 0.61$, no interaction of response compatibility with SOA, $F(2, 90) = 0.2$. The interaction of response compatibility and experimental group was not significant, $F(2, 45) = 1.98$, $p = 0.150$, although a numerical response compatibility effect was present in Experiment 2C, but was absent or reversed in Experiments 2A and 2B. These results support the observation of early SOA-focused response compatibility effects in Before phase data across all experiment groups, and the general absence of response compatibility effects during the Interference phase.

Next, we compared Task 1 RT Interference data with data from the After phase, across all experiment groups. We observed interactions of response compatibility and SOA, $F(2, 90) =$

3.37, $p < 0.05$, and of response compatibility, SOA and experiment phase, $F(2, 90) = 5.69$, $p < 0.01$, supporting the observation of early SOA-focused response compatibility effects in After phase data, compared to the general absence of response compatibility effects in the Interference phase. Assessing just After data revealed a strong interaction of response compatibility and SOA, $F(2, 90) = 9.43$, $p < 0.001$, confirming the observed response compatibility effects maximal at the earliest SOA. A marginal interaction of SOA, response compatibility and experimental group, $F(4, 90) = 2.14$, $p = 0.083$, suggested that the response compatibility effect at 0 ms SOA in Experiment 2C may have been larger than those for Experiments 2A and 2B. Limiting our analysis of After data further to only 0 ms SOA data revealed a non-significant interaction of response compatibility and experimental group, $F(2,45) = 2.20$, $p = 0.123$.

As a direct assessment of the influence of our Interference phase on subsequent practiced PRP performance, we assessed Before versus After data across all experiment groups. We observed no interaction of experiment phase and response compatibility, $F(1, 45) = 1.05$, $p = 0.312$, and no interaction of these factors with experiment group, $F(2, 45) = 0.045$, $p = 0.96$.

Finally, inspection of mean RT1 data in Figure 5 confirmed our prediction of an apparent numerical response compatibility effect in the interference phase of Experiment 2C (unrelated Task 2), compared to interference data from Experiments 2A (conflict Task 2 mapping) and 2B (reversed Task 2 mapping) showing numerically reversed response compatibility effects at early SOAs. While the omnibus ANOVA and overall assessment of Interference phase data did not support these differences statistically, we conducted a final directed analysis to investigate our a priori predictions of this particular pattern of data. As reported above, the interaction of response compatibility across experimental groups for Interference phase data was not significant, $F(2, 45) = 1.98$, $p = 0.150$. Data from the Interference block for Experiment 2C alone showed a marginal effect of response compatibility, $F(1, 15) = 3.15$, $p = 0.096$, in comparison to absent or reversed response compatibility effects in Experiment 2A and 2B data, *F*s < 0.3.

Task 2 RT

For Task 2 RT data, very similar patterns of effects of response compatibility were observed as for Task 1 RT. The omnibus ANOVA for Task 2 RT revealed a strong main effect of SOA, $F(2, 90) = 1242.58$, $p < 0.001$, as expected in a PRP paradigm. Main effects of experiment phase, $F(2, 90) = 14.64$, $p < 0.001$, and response compatibility, $F(1, 45) = 4.17$, $p < 0.05$, were also observed. These main effects were modified by interactions of SOA and experiment phase, $F(4, 180) = 3.18$, $p < 0.05$, and SOA and response compatibility, $F(2, 90) = 6.12$, $p < 0.01$, and the three-way interaction of these factors, $F(4, 180) = 2.84$, $p < 0.05$. Experiment group was also observed to interact with response compatibility, $F(2, 45) = 3.23$, $p < 0.05$, and with SOA and experiment phase, $F(8, 180) = 3.55$, $p < 0.001$.

This pattern of effects supported the observation of response compatibility effects, most prominent at the shortest SOA, across all experiment groups in Before and After phases, but generally absent in the Interference phase. We again observed an apparent difference in response compatibility effects between Experiment 2C and the other experiment groups in the Interference phase, although this contrast was not statistically significant in Task 1 RT. We again conducted a set of targeted post-hoc analyses to examine effects suggested by the omnibus ANOVA above, plus a direct test of between-groups differences in the Interference phase data, following our treatment of and findings from Task 1 RT data. We report here only the critical distinguishing effects not already evident from the omnibus ANOVA above.

First, we repeated our ANOVA comparing data from only Before and Interference phases. We observed an interaction of response compatibility and experiment group, $F(2, 45) =$

3.40, $p < 0.05$, but no interactions of these factors with experiment phase, $Fs < 1.2$. Considering Before data alone, we observed a main effect of response compatibility, $F(1, 45) = 9.25$, $p < 0.01$, and an interaction of response compatibility and SOA, $F(2, 90) = 6.56$, $p < 0.01$, with no interactions of response compatibility and experiment group, $Fs < 0.75$. These effects confirm our observations of robust response compatibility effects in Before data, larger at earlier SOAs. Considering just the Interference data, we observed an interaction of response compatibility and experiment group, $F(2, 45) = 3.54$, $p < 0.05$, with no main effect of response compatibility, $F(1, 45) = 0.30$. These effects confirm our observation of response compatibility effects in Experiment 2C data, with absent or reversed response compatibility effects in Experiment 2A and 2B data.

Next, we compared data from the Interference phase with data from the After phase. We observed an interaction of response compatibility with experiment group, $F(2, 45) = 3.73$, $p < 0.05$, reflecting a larger overall response compatibility effect in Experiment 2C versus other groups, and an interaction of experiment phase, SOA and response compatibility, $F(2, 90) = 4.40$, $p < 0.05$, reflecting larger response compatibility effects in the After phase, largest at the earliest SOA. Considering just the After data, we observed a clear interaction of SOA and response compatibility, $F(2, 90) = 8.92$, $p < 0.001$, reinforcing the localization of response compatibility effects at early SOA in After phase data.

Finally, as a direct assessment of the influence of our Interference phase on subsequent practiced PRP performance, we compared data from Before and After phases. We observed a main effect of response compatibility, $F(1, 45) = 6.98$, $p < 0.05$, and an interaction of response compatibility and SOA, $F(2, 90) = 14.70$, $p < 0.001$, with no interactions of response compatibility and experiment phase, $Fs < 1.4$.

Errors

Mean error rate data for Task 1 and Task 2 are summarized in Table 2. Given our focus on response compatibility effects in reaction time data, for the sake of brevity we again present a basic reporting and analysis of error data, beyond testing our critical response compatibility data for potential speed-accuracy trade-off effects. Overall, the substantial majority of errors were again committed on Task 2. In Task 1, we observed a strong response compatibility effect, $F(1,45) = 20.15$, $p < 0.001$, with fewer errors on response compatible versus incompatible trials, mirroring the general RT findings and showing no evidence of a speed-accuracy trade-off in Task 1. Again similar to Experiment 1, errors were most frequent at 0 ms SOA, and decreased as SOA increased, $F(2, 90) = 12.80$, $p < 0.001$. SOA and response compatibility interacted, with largest response compatibility differences at 0 ms SOA, reducing to small or non-existent differences at 800 ms SOA, $F(2, 90) = 9.44$, $p < 0.001$. For Task 2 error data, a strong reverse response compatibility was observed, $F(1, 45) = 17.35$, $p < 0.001$, with response compatible trials more errorful than incompatible trials across all conditions. A main effect of SOA reflected reduced errors as SOA increased, $F(2, 90) = 6.83$, $p < 0.01$, akin to the effect of SOA on errors in Task 1. These Task 2 error effects again replicated the general pattern of error data observed in Experiment 1.

Discussion

In Experiment 2 we sought to dissociate an episodic account of backward response compatibility from a working memory account by temporarily altering response mapping in a typical PRP paradigm, and comparing response compatibility effects before, during, and after this interference phase. In the initial Before phase, participants across three separate experimental groups all performed 288 trials (nine 32-trial mini-blocks) of the same PRP dual task, responding to shapes as Task 1, and responding to whether single digits were numerically higher or lower than 5 as Task 2, using the same two manual response alternatives to respond in turn to each task. Response compatibility effects were observed on Task 1 RT in these Before data, strongest at 0 ms SOA, across all three experimental groups.

In the subsequent 96-trial Interference phase, each experimental group continued to perform a PRP task, but with a modified Task 2 for each group than in the initial Before phase. In experiment 2A, participants received the same Task 2 digit stimuli, but responded as to whether digits were odd or even; in Experiment 2B, participants again judged digits as higher or lower than 5, but with the response mapping reversed compared to the Before PRP Task 2. In both of these cases, backward response compatibility effects were abolished in Interference phase data, with many of these effects numerically reversed. In contrast, in Experiment 2C, where the Interference phase Task 2 asked participants to respond to colour patches, a marginal response compatibility effect was observed on Task 1. In the final 96-trial After phase, all three groups performed the same original PRP dual task from the Before phase. Response compatibility effects were again observed on Task 1 RT as in the Before data, strongest at 0 ms SOA, across all three experimental groups.

The presence of backward response compatibility effects in both the Before and After phases, but not during Interference (in high-conflict Task 2 groups, Experiment 2A and 2B) support the assumptions of an episodic account of response compatibility. Under a primarily working memory model, response compatibility effects would be predicted in the Interference phase, since old S-R rules held online should be immediately replaced by the S-R rules of the new task set. Even if it could be argued that the 96 trials of the Interference phase were too short to fully instantiate the new task rules in working memory, then a purely working memory account still could not explain the strong reappearance of these effects in the After phase, which was identical in length. Instead, the lack of response compatibility effects in the Interference phase and their return in the subsequent After phase suggests that learned S-R (or C-R) associations from the substantially longer Before phase provided proactive interference for conflicting S-R mappings during Interference, and that these original S-R associations were stable enough in memory to be retrieved when the original task context was reinstated.

The presence of Task 2 response compatibility effects again closely followed those seen in Task 1, suggesting that these Task 2 effects may have been primarily locus of slack carryover effects reflecting primary differences in Task 1 RT processing. Considering this possibility, we note that the response compatibility effect in the Interference phase of Experiment 2C (low-conflict Task 2) that was marginally significant in Task 1 RT was observed to be reliable in Task 2 RT. This suggests potential additional support for the notion that response compatibility effects can emerge relatively quickly through episodic learning amongst varied task performance, in the absence of strong interference on to-be-acquired S-R (or C-R) task mappings.

The Before and Interference phases of Experiment 2B provide a direct replication of Hommel and Eglau's (2002) Experiment 4. They showed that backward compatibility effects observed in the first half of trials disappeared in the second half of trials when the S-R mapping in Task 2 was reversed. Each experiment half consisted of 100 trials, which is equivalent to the length of the Interference phase of the present experiment (96 trials). Hommel and Eglau argued that once S-R associations are acquired, these connections make it difficult to associate the same codes in different ways. Even though it is likely that backward compatibility effects would emerge under the new response mapping with a sufficient amount of practice, the results of Hommel and Eglau suggest that the amount of practice required is potentially greater than that needed to acquire the original associations. The After phase of the present experiment extends the work of Hommel and Eglau to show that these originally learned S-R associations are rapidly recovered after performing an intervening task with conflicting S-R mapping. Ultimately, these findings provide strong evidence in favour of the critical role of learning and episodic memory for automatic S-R translation and backward response compatibility effects in dual tasks.

GENERAL DISCUSSION

This study sought to specify the mechanism underlying the backward response compatibility effect in the PRP paradigm. A working memory-mediated, or transient-link model presumes that backward compatibility effects arise from automatic S-R or C-R translation resulting from holding multiple S-R (or C-R) response rules online in working memory (Ellenbogen & Meiran, 2008). Work from task-switching (Allport & Wylie, 1999, 2000; Wylie & Allport, 2000; Waszak, Hommel, & Allport, 2002) and dual task processing (Hommel & Eglau, 2002) literatures suggest a critical role for an episodic memory-mediated, or a direct-link model of automatic S-R or C-R translation. Using a typical PRP paradigm we examined the role of learning by providing participants with varying degrees of single task practice prior to a common dual task phase in Experiment 1, and contrasted the predictions of working memory and episodic learning in Experiment 2 by interfering with previously learned S-R associations with either conflicting or non-conflicting S-R mapping.

Overall, our findings support an episodic account of the generation of backward response compatibility effects. In Experiment 1 we found that participants who previously practiced both component tasks of a dual task procedure showed backward response compatibility effects earlier in PRP dual task performance than participants who had no prior experience with either task, suggesting a critical role for the learning and subsequent influence of episodic S-R associations. In Experiment 2 we showed that backward response compatibility effects present in an initial learning phase disappeared when conflicting or reversed response mappings were introduced, and reappeared when the original PRP task was reinstated. These results cannot easily be explained by a working memory account of backward response compatibility effects, which would instead predict that prior episodic S-R information acquired over practice should have relatively little influence on the response compatibility effects generated via task rule-related S-R links held online in working memory, and that backward compatibility effects should very rapidly follow the successful instantiation of new task rules in working memory.

Our results follow and extend Hommel and Eglau (2002) who forwarded an episodic account of backward compatibility effects after demonstrating that, once S-R associations are learned, backward compatibility effects persist even when Task 2 is no longer performed (Experiment 3), and that effects disappear when Task 2 response mapping is reversed (Experiment 4). Our work replicates Hommel and Eglau's Experiment 4, and presents additional evidence that compatibility effects return after the originally learned response mapping is re-introduced. Moreover, we show that the magnitude of the compatibility effect after this interference did not differ significantly from the magnitude of the effect prior to interference, supporting the idea that initially learned S-R or C-R associations may be relatively protected from destructive interference by conflicting task mappings.

We suggest that working memory does play an important role in the development of backward response compatibility effects, but that this role is related to the acquisition and episodic learning of Task 2 S-R and C-R pairings, and that this predominantly (perhaps exclusively) occurs during the overt and attended performance of Task 2 within a PRP paradigm.

As Task 2 S-R or C-R mappings are learned and represented more strongly over numbers of trials, we suggest that backward response compatibility effects emerge during overt Task 1 performance due to the rapid and unintentional stimulus-driven retrieval of Task 2 response information (when a Task 2 stimulus is available close in time, typically at short SOAs), in parallel with effortful Task 1 performance. We speculate that the disruption of backward compatibility effects with very high working memory loads (implemented by having a large number of S-R or C-R mapping rules for Task 1) reported by Ellenbogen and Meiran (2008) may be due to the relative disruption of acquiring sufficient episodic representations with relatively fewer experiences per stimulus or category. Alternatively, the degree of learning of particular S-R or C-R associations on any given trial may have been smaller with very high working memory loads if some rules were not optimally represented on the relevant trials—assuming a limited working memory capacity that is being pushed towards some conservative limit, the probability of this occurrence should increase with larger numbers of task rules.

Finally, we note that one piece of evidence often claimed as necessitating a working memory account – the rapid appearance of backward response compatibility in PRP data with minimal practice – is not incompatible with an episodic mechanism. Work over the past decade on context-sensitive effects of episodic memory (e.g., Hommel, 2004), and comparable ideas including contextual item-specific and stimulus-task bindings producing proactive interference in task switching (e.g., Allport & Wylie, 2000; Waszak, Hommel & Allport, 2003), has shown the ability for a very small number of prior trials to influence speeded performance on later trials with sufficient overlap of task and trial context. We suggest that similar episodic effects are a reasonable assumption here, and that these ideas are also consistent with the response compatibility and transient disruption of response compatibility effects in the present paper and elsewhere.

The results of this study both provide data to address questions in the literature on models of backward response compatibility, and provide further evidence for the existence of parallel central response processing during dual task performance. Particularly, we have attempted to better define the mechanisms by which backward response compatibility, and thus in part central parallel response processing, occurs by demonstrating a critical role for episodic retrieval. Such work has implications for the understanding of parallel processing mechanisms, as well as general models of selective attention and cognitive control, and the limitations and abilities inherent in dual task processing.

REFERENCES

Allport, A., & Wylie, G. (1999). Task-switching: Positive and negative priming of task-set. In G.W. Humphreys, J. Duncan, & A.M.Treisman (Eds.), *Attention, space and action: Studies in cognitive neuroscience* (pp. 273 – 296). Oxford: Oxford University Press.

Allport. A., & Wylie, G. (2000). 'Task-switching', stimulus-response bindings and negative priming. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance XVII* (pp. 35 – 70). Cambridge, MA: MIT Press.

Ellenbogen, R. & Meiran, N. (2008). Working memory involvement in dual task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36*, 968-978.

Hazeltine, E., Teague, D., & Ivry, R.B. (2002). Simultaneous dual task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 527-545.

Hommel, B. (1998). Automatic stimulus-response translation in dual task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1368-1384.

Hommel, B. (2004). Event files: feature binding in and across perception and action. *TRENDS in Cognitive Science, 8*, 494 – 500.

Koch, I. (2009). The role of crosstalk in dual task performance: Evidence from manipulating response-code overlap. *Psychological Research, 73,* 417-424.

Logan, G.D., Miller, A.E., & Strayer, D.L. (2011). Electrophysiological evidence for parallel response selection in skilled typists. *Association for Psychological Science, 22*, 54-56.

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

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research-psychologische Forschung, 70*, 484 – 493**.**

Miller, J. & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 149 – 165.

Pashler, H. (1992). Attentional limitations in doing two tasks at the same. *Current Directions in Psychological Science, 1*. 44-48.

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

Reynvoet, B., Cassens, B., & Brysbaert, M. (2002). Automatic stimulus-response associations may be semantically mediated. *Psychonomic Bulletin & Review, 9*, 107 – 112.

Ruthruff, E., Johnston, J.C., & Remington, R.W. (2009). How strategic is the central bottleneck: Can it be overcome by trying harder? *Journal of Experimental Psychology: Human Perception and Performance, 35*, 1368-1384.

Ruthruff, E., Johnston, J.C., & Van Selst, M. (2001). Why practice reduces dual task interference. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 3-21.

Ruthruff, E., Pashler, H.E., & Hazeltine, E. (2003). Dual task interference with equal task emphasis: Graded capacity sharing or central postponement? *Perception & Psychophysics, 65*, 801-816.

Ruthruff, E., Pashler, H.E., & Klaassen, A. (2001). Processing bottlenecks in dual task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review, 8*, 73-80.

Ruthruff, E., Van Selst, M., Johnston, J.C., Remington, R. (2006). How does practice reduce dual task interference: Integration automatization, or just stage-shortening? *Psychological Research, 70*, 125-142.

Schumacher, E.H., Seymour, T.L., Glass, J.M., Fencsik, D.E., Lauber, E.J., Kieras, D.E., & Meyer, D.E. (2001). Virtually perfect time-sharing in dual task performance: Uncorking the central cognitive bottleneck. *Psychological Science, 12*, 101-108.

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

Thomson, S.J., Watter, S., & Finkelshtein, A. (2010). Parallel response selection in dual task situations via automatic category-to-response translation. *Attention, Perception, & Psychophysics, 72*, 1791 – 1802.

Tombu, M. & Jolicoeur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 795-810.

Van Selst, M.A., Ruthruff, E., & Johnston, J.C. (1999). Can practice eliminate the Psychological Refractory Period effect? *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1268 – 1283.

Waszak, F., Hommel, B., & Allport, A. (2003). Task-switching and long-term priming: Role of episodic stimulus-task bindings in task-shift costs. *Cognitive Psychology, 46,* 361-413.

Watter, S. & Logan, G.D. (2006). Parallel response selection in dual task situations. *Perception & Psychophysics, 68*, 254-277.

Welford, A.T. (1952). The 'Psychological Refractory Period' and the timing of high-speed performance – A review and a theory. *British Journal of Psychology: General Section, 43*, 2 – 19.

Wylie, G., & Allport, A. (2000). Task switching and the measurement of "switch costs". *Psychological Research, 63,* 212 – 233.

Table 1
Mean Dual task Error Rates (%Err) and Standard Errors of the Means (SE) for Experiment 1A – 1D

	Task1				Task2			
	Resp+		Resp-		Resp+		Resp-	
SOA	%Err	SE	%Err	SE	%Err	SE	%Err	SE
Experiment 1a								
0	2.26	0.01	9.51	0.02	10.59	0.01	5.87	0.01
200	0.92	0.003	3.27	0.01	9.71	0.01	5.57	0.01
800	1.44	0.005	1.85	0.01	10.71	0.02	3.72	0.01
Experiment 1b								
0	3.38	0.01	5.88	0.01	11.05	0.02	6.72	0.01
200	2.98	0.01	4.57	0.01	11.47	0.02	6.24	0.01
800	2.49	0.01	2.32	0.01	9.44	0.01	3.48	0.01
Experiment 1c								
0	2.06	0.01	4.39	0.01	11.15	0.02	8.23	0.01
200	1.29	0.005	2.18	0.005	11.33	0.01	7.63	0.02
800	1.83	0.01	2.73	0.01	9.58	0.02	5.36	0.01
Experiment 1d								
0	4.73	0.01	6.27	0.01	10.94	0.02	5.57	0.02
200	3.33	0.01	5.27	0.02	10.36	0.02	3.58	0.01
800	3.48	0.01	3.45	0.01	10.67	0.02	2.77	0.01

Table 2
Mean Dual task Error Rates (%Err) and Standard Errors of the Means (SE) for Experiment 2A-2C

	Before								Interference								After							
	Task1				Task2				Task1				Task2				Task1				Task2			
	Resp+		Resp-		Resp+		Resp-		Resp+		Resp-		Resp+		Resp-		Resp+		Resp-		Resp+		Resp-	
SOA	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE	%Err	SE
Experiment 2a																								
0	2.70	0.01	7.65	0.02	9.37	0.03	9.19	0.03	1.59	0.01	5.21	0.02	15.32	0.04	11.96	0.03	1.17	0.01	5.19	0.01	7.01	0.03	4.99	0.02
200	2.38	0.01	3.56	0.01	9.81	0.01	6.29	0.02	2.73	0.01	1.61	0.01	11.29	0.03	11.36	0.03	1.68	0.01	0.39	0.004	6.89	0.02	2.37	0.01
800	2.28	0.01	3.50	0.01	5.65	0.01	4.72	0.02	0.81	0.01	1.56	0.01	10.76	0.03	11.24	0.03	1.56	0.01	0.39	0.004	2.57	0.01	2.37	0.01
Experiment 2b																								
0	2.14	0.01	5.67	0.01	11.86	0.02	6.42	0.01	3.15	0.01	4.30	0.02	16.34	0.03	9.30	0.03	1.17	0.01	3.52	0.01	9.97	0.03	5.13	0.02
200	1.72	0.01	3.40	0.01	9.01	0.02	4.48	0.01	2.00	0.01	1.80	0.01	12.45	0.03	8.63	0.02	1.95	0.01	2.73	0.01	7.66	0.02	2.87	0.01
800	3.23	0.01	2.64	0.01	11.49	0.03	4.30	0.01	1.17	0.01	0.78	0.005	10.42	0.03	8.53	0.03	0.87	0.01	1.56	0.01	8.46	0.03	3.26	0.01
Experiment 2c																								
0	2.68	0.01	5.93	0.01	10.83	0.02	9.52	0.02	4.78	0.02	2.17	0.01	12.47	0.04	6.16	0.02	2.79	0.01	8.23	0.02	5.39	0.02	5.25	0.01
200	2.26	0.01	5.36	0.01	11.22	0.01	8.03	0.02	2.98	0.01	3.65	0.02	10.29	0.02	8.81	0.03	2.34	0.01	4.30	0.01	9.67	0.03	5.03	0.02
800	2.11	0.01	2.66	0.01	12.82	0.03	6.27	0.01	2.20	0.01	1.40	0.01	7.69	0.03	3.63	0.01	3.12	0.02	1.64	0.01	6.25	0.02	2.51	0.01

Figure Captions

Figure 1. Standard response selection bottleneck (RSB) model of dual task processing. The RSB model (A) suggests that response selection stages (shaded area) do not overlap between tasks. A modified RSB model (B) suggests that Task 2 response information can be generated in parallel with Task 1 response information, generating backward response compatibility effects (Task 2-to-Task 1 response priming).

Figure 2. Experimental design of Experiment 1. Participants in each experimental group (1A to 1D) received four rounds of Single Task practice (two sets of two single tasks, in counterbalanced order), followed by a common Dual Task PRP phase. Across groups, participants received single task practice on both Task 1 (*shape*) and Task 2 (*colour*) of the final PRP dual Task (1A), on only Task 2 plus a filler task (*case*) (1B), on only Task 1 plus a filler task (*case*) (1C), or on two filler tasks (*case* and *size*) (1D).

Figure 3. Task 1 and Task 2 reaction time (RT) data for Experiment 1. Task 1 and Task 2 reaction time (RT) data for Experiment 1 PRP dual task data, separated by stimulus onset asynchrony (SOA) and Task 1 to Task 2 response compatibility, separately for each experimental group (1A to 1D). Task 1 RTs for response compatible trials were faster than incompatible trials, most strongly at the 0 ms SOA, indicating the presence of Task 1 compatibility effects (Task 2-to-Task 1 priming). This effect was most prominent in Experiment 1A and 1D, versus 1B and 1C groups.

Figure 4. Task 1 and Task 2 reaction time (RT) data for Experiment 1A and 1D. Task 1 and Task 2 reaction time (RT) data for Experiment 1A and 1D PRP dual task data, separated by stimulus onset asynchrony (SOA) and Task 1 to Task 2 response compatibility, separately for experimental session half. Response compatibility effects on Task 1 were observed in the first

and second halves of Experiment 1A, most strongly at the 0 ms SOA, following prior single task practice of both PRP component tasks. In contrast, backward response compatibility effects were notable only in the second half of Experiment 1D, with no prior single task practice of PRP component tasks.

Figure 5. Task 1 and Task 2 reaction time (RT) data for Experiment 2. Task 1 and Task 2 reaction time (RT) data for Experiment 2, separated by stimulus onset asynchrony (SOA) and Task 1 to Task 2 response compatibility, plotted separately for experimental phase (Before, Interference, After), and experimental group (2A, 2B 2C). Response compatibility effects on Task 1 were observed, most strongly at 0 ms SOA, during the Before and After phases of all experimental conditions, and marginally during the Interference phase of Experiment 2C with minimal overlap of alternative Task 2 response mapping. In contrast, backward response compatibility effects were abolished in the Interference phase of Experiment 2A and 2B, with high-conflict and reversed (respectively) alternative Task 2 response mappings. These data are consistent with an episodic mediation account of backward response compatibility.

Figure 1. Standard response selection bottleneck (RSB) model of dual task processing.

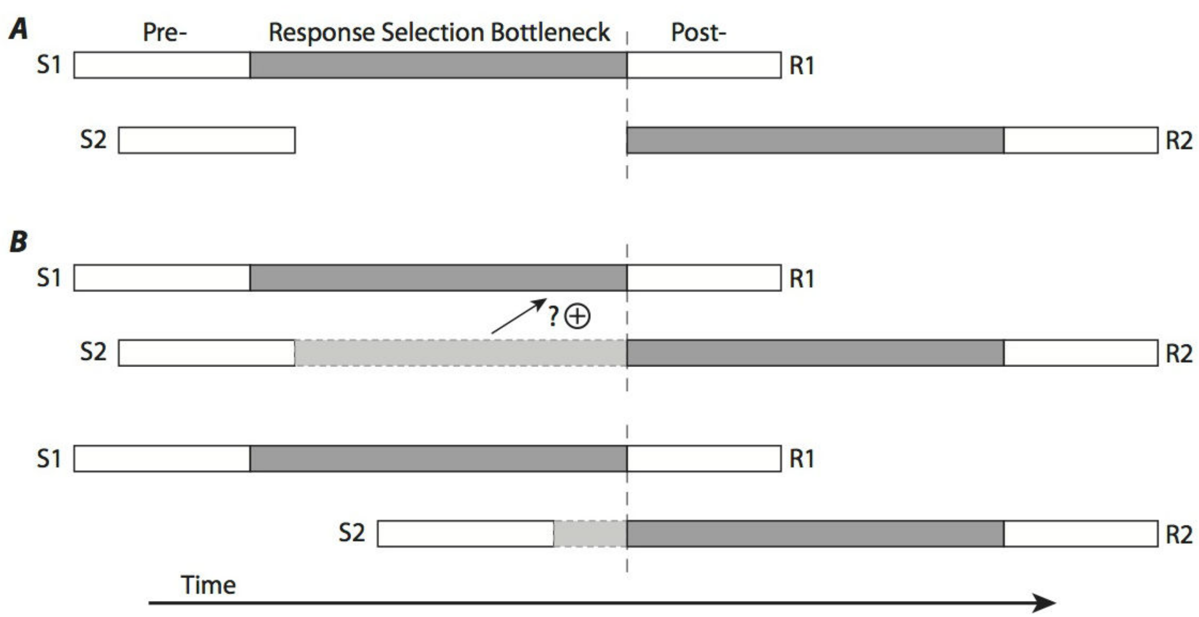

Figure 2. Experimental design of Experiment 1.

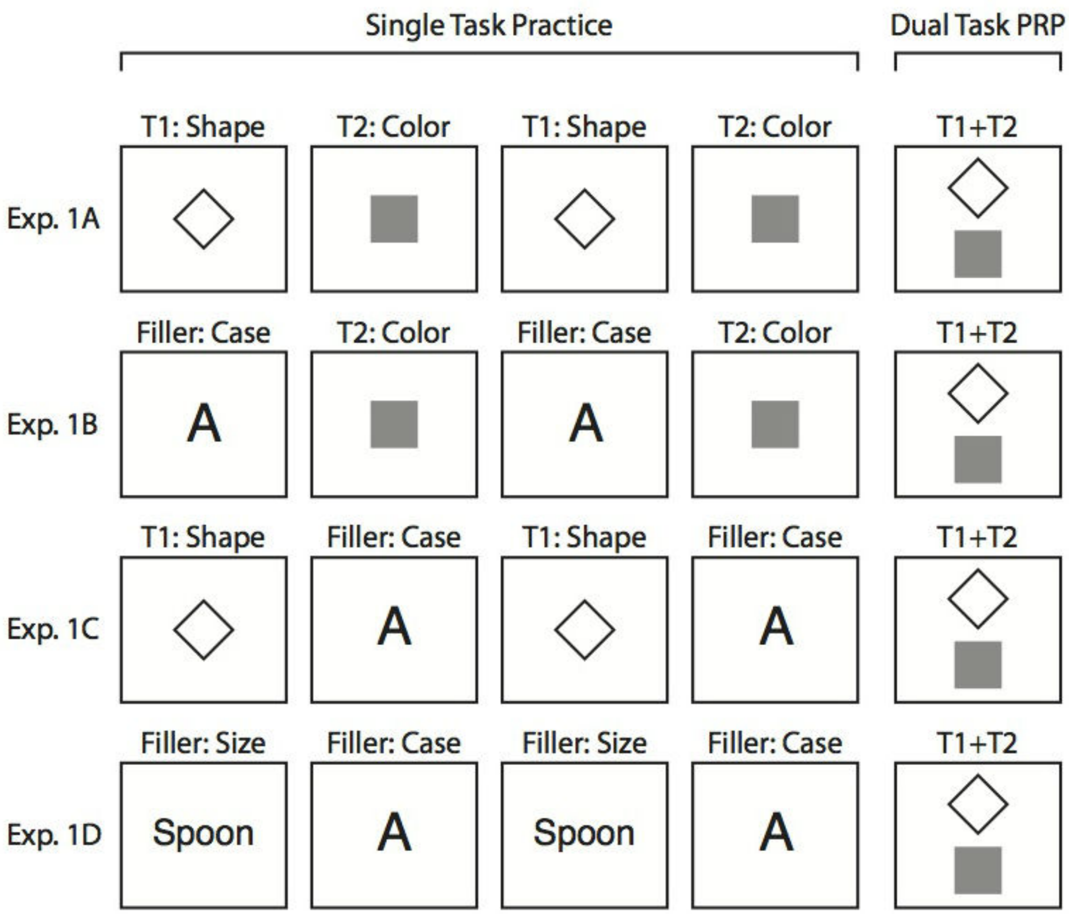

Figure 3. Task 1 and Task 2 reaction time (RT) data for Experiment 1.

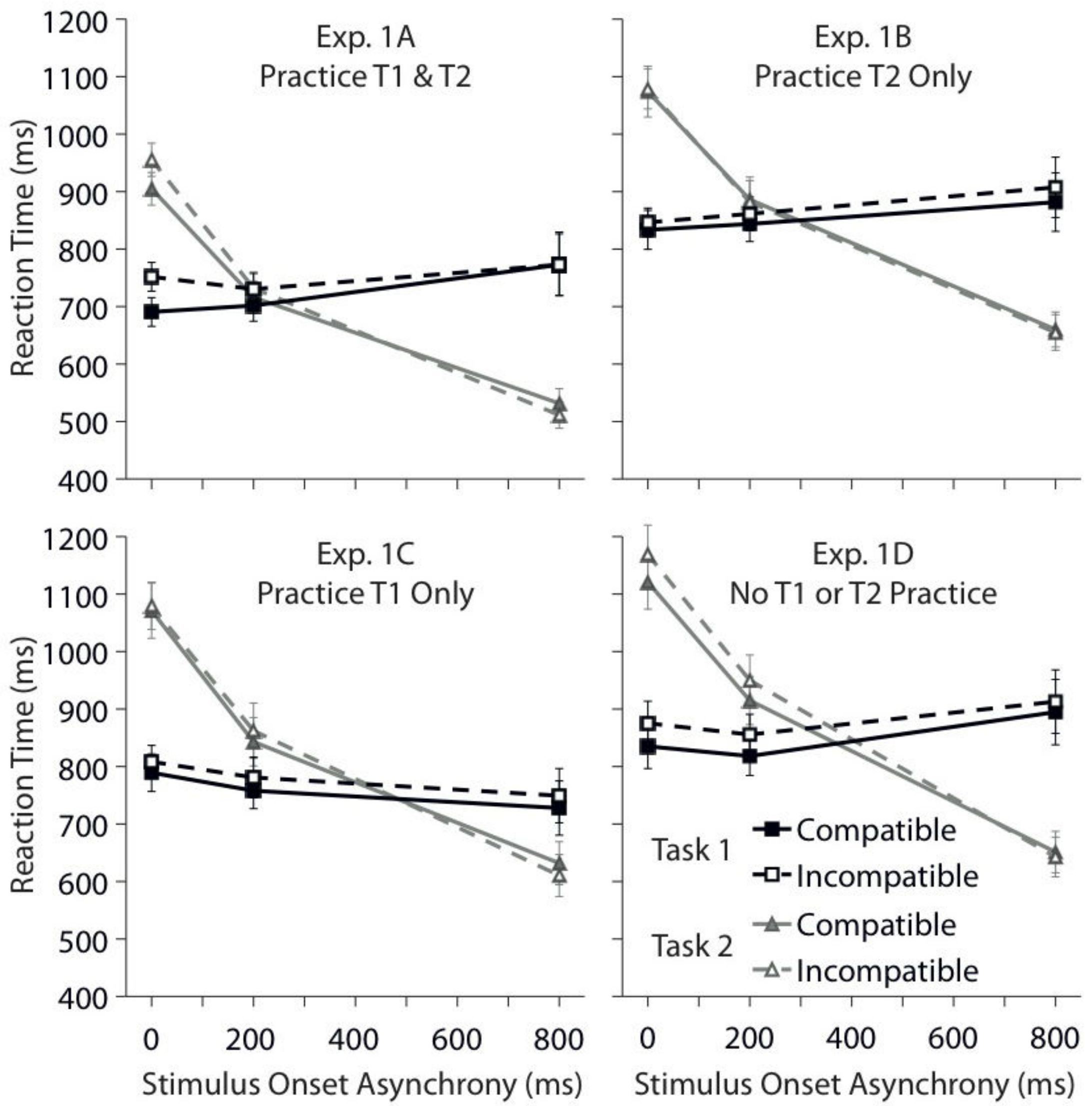

Figure 4. Task 1 and Task 2 reaction time (RT) data for Experiment 1A and 1D.

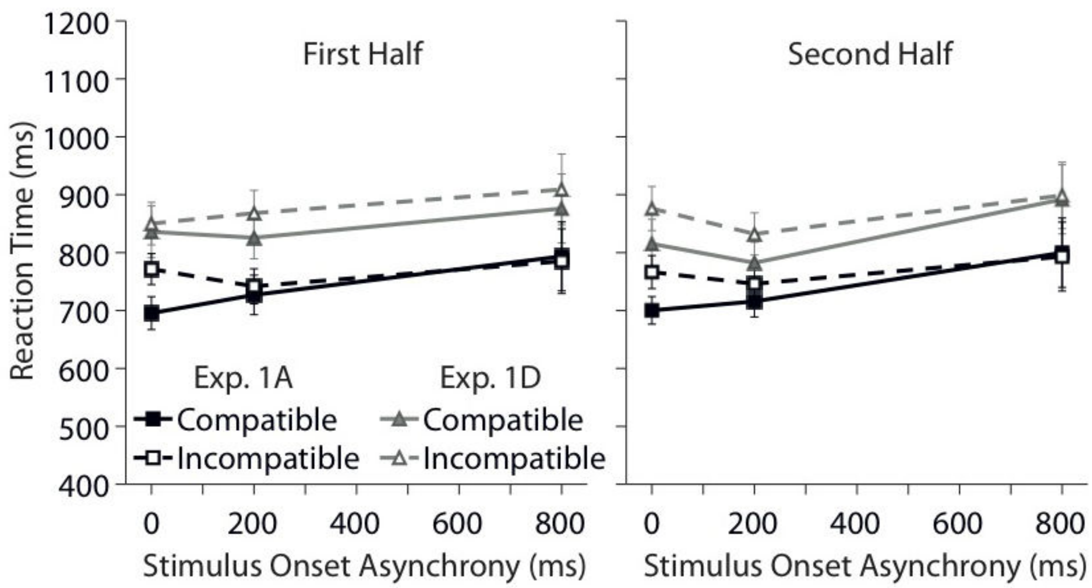

Figure 5. Task 1 and Task 2 reaction time (RT) data for Experiment 2.