BACKWARD COMPATIBILITY EFFECTS IN DUAL-TASK PERFORMANCE

BACKWARD COMPATIBILITY EFFECTS IN DUAL-TASK PERFORMANCE: IMPLICATIONS FOR CENTRAL INFORMATION PROCESSING

By SANDRA JEAN THOMSON, B.Sc. (HONOURS)

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AUTHOR: Sandra Jean Thomson, B.Sc. (Honours) (McMaster University)

SUPERVISOR: Dr. Scott Watter

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Abstract

The psychological refractory period (PRP) paradigm has been used extensively to investigate the cognitive processing stages involved in dual-task performance. Interpretations of PRP data have often attributed the difficulty in simultaneously performing two cognitive tasks to a strict serial processing bottleneck in the response selection stage. However, a number of studies have also demonstrated backward response compatibility effects (BCEs) on Task 1 reaction time in dual-task performance, which suggest that response information for Task 2 may be activated in parallel with Task 1 response selection. The goal of this thesis was to examine the nature of the Task 2 processing that operates in parallel with Task 1 response selection in a PRP task, and to consider the implications of this parallel processing for models of dual-task performance. The results of the empirical studies presented here provide converging evidence that the BCE represents automatically activated response information for Task 2 acting on Task 1 response selection. This Task 2 response information can also contribute to Task 2 performance. Models of dual-task performance must account for both the parallel activation of response information and the serial selection of a response for each task.

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Table of Contents

List of Figures

Figure Number **Page Number**

Chapter 2

Chapter 3

Chapter 4

Chapter 5

List of Tables

Table Number **Page Number**

Chapter 2

Chapter 3

Chapter 4

Abbreviations and Symbols

Abbreviation	**Definition**
BCE	backward compatibility effect
C-R	category-to-response
ECTVA	executive control theory of visual attention
EPIC	executive process interactive control
IRI	interresponse interval
ms / msec	millisecond
PRP	psychological refractory period
R1	response to Task 1
R2	response to Task 2
RSB	response selection bottleneck
RT	reaction time
RT1	reaction time for Task 1
RT2	reaction time for Task 2
S-R	stimulus-to-response
S1	stimulus for Task 1
S2	stimulus for Task 2
S2a	transient prime stimulus for Task 2
S2b	target stimulus for Task 2
SOA	stimulus onset asynchrony
SRD	strategic response deferment
TVA	theory of visual attention

Declaration of Academic Achievement

This is a ‘sandwich’ thesis, which consists of three studies designed to investigate the basic cognitive processes that support dual-task performance. Chapters 2 and 4 have been published in a peer-reviewed journal, and Chapter 3 has been submitted for peer-review. I am the first author of each empirical chapter.

Chapter 2 is a reprint of 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. This work was completed in collaboration with my thesis supervisor as well as honours thesis student Anna Finkelshtein, from 2008-2009. I supervised Anna in the creation of stimuli, data collection, and analysis for one experiment while I was responsible for the other. I also programmed the experiments, completed more advanced analyses, and prepared the original manuscript and the first draft of the revision, with useful input from Dr. Watter.

Chapter 3 is a manuscript that has been submitted for publication: Thomson, S. J., Danis, L. K., & Watter, S. (submitted July 15, 2013; manuscript ID PBR-BR-13-200). PRP training shows task1 response selection is the locus of the backward response compatibility effect. *Psychonomic Bulletin & Review.* I designed and programmed the experiments and supervised Lila Danis, who collected the data for Experiment 1 for her honours thesis in 2011-2012. I oversaw the follow up experiment and performed the majority of the data analysis. I am the primary and corresponding author for the paper.

Chapter 4 is a reprint of Thomson, S. J., & Watter, S. (2013). Information continuity across the response selection bottleneck: Early parallel response selection for unattended tasks influences later overt responses. *Attention, Perception & Psychophysics, 75*, 934-953. This work was completed in collaboration with my thesis supervisor. Both authors contributed substantially to the experimental design. I led the research investigation which first began in 2007, including data collection and analysis, and wrote the first drafts of the original manuscript and all subsequent revisions.

CHAPTER 1

Introduction

People often try to multitask to cope with the busyness of everyday life. But to what extent are we actually able to do two things at once? Subjectively, it often feels difficult or less efficient to perform two cognitive tasks simultaneously, but what are the actual constraints on dual-task performance? Cognitive psychologists have been interested in the capacities and limitations involved in human information processing for a very long time. Most of the work done in this field has pointed to a processing bottleneck that requires that a central stage in processing be performed only for one task at a time. Typically, this bottleneck is presumed to be in the stage of response selection (Pashler, 1984; 1994; Pashler & Johnston, 1998), where stimuli are mapped to responses according to the task rules. The purpose of this thesis is to examine whether response selection processing for two tasks may in fact proceed in parallel, and to determine the consequent implications for models of dual-task performance.

The Psychological Refractory Period Paradigm

Dual-task performance is often studied using variations of the Psychological Refractory Period (PRP) paradigm. The name originates from Telford (1931), who was among the first to measure serial reaction times to stimuli separated by a variable stimulus onset asynchrony (SOA). Telford found that at short SOAs (500 ms) participants took much longer to respond to the second stimulus compared to when the SOA was longer (1000 or 2000 ms). He described a period of “intrinsic unreadiness for response” that followed the initial response, and compared this to the refractory phase observed in the nervous system. While this analogy may not be accurate, the term psychological refractory period has remained.

In a typical PRP paradigm, participants are presented with two stimuli (S1 and S2) separated in time by a variable SOA, usually between 0 and 1000 ms. Participants are asked to make a speeded response to each stimulus according to its task set rules (i.e., make response R1 to S1 to complete Task 1 and make response R2 to S2 to complete Task 2), often with special priority given to the completion of Task 1. The highly robust finding in such studies is that the reaction time to Task 1 (RT1) is unaffected by SOA while the reaction time to Task 2 (RT2) increases with decreasing SOA, approaching a slope of -1 at very short SOAs. The cost to Task 2 performance at short SOAs is known as dual-task interference. This interference is extremely difficult, if not impossible, to overcome even after substantial amounts of PRP practice (Ruthruff, Johnston, & Van Selst, 2001; Van Selst, Ruthruff, & Johnston 1999).

The Response Selection Bottleneck (RSB) Model

Welford (1952) interpreted this pattern of results as demonstrating that some phase of processing for the two tasks cannot overlap, leading to a bottleneck in processing. He predicted that this bottleneck occurred in the central processing mechanism of selecting a response for each task, which he referred to as “organizing time”. Pashler (1984) later followed up on this idea and conducted a series of elegant experiments converging on the notion that Welford was correct in his postulation of a response selection bottleneck. He assumed that the processing of a task could be divided into successive stages that are serial and discrete, meaning that a stage cannot begin until the previous stage has been completed (Sternberg, 1969). With overlapping tasks, processing can proceed for both tasks in parallel until the bottleneck stage is reached, whereas the bottleneck stage can only be completed for one task at a time. This serial requirement for the bottleneck stage postpones processing in the second task, which must wait for access to the bottleneck stage until this stage of processing is complete for Task 1. Pashler (1984) convincingly demonstrated that the bottleneck occurred in the central stage of response selection, rather than earlier perceptual or later motor stages. He manipulated the duration of early stages of Task 2 processing by varying stimulus contrast, and found effects that were underadditive with SOA, suggesting that this effect was absorbed into the "slack" (Schweickert, 1978; Schweickert & Townsend, 1989; Townsend & Schweickert, 1989), while Task 2 central processing was delayed by the bottleneck. Subsequent studies have shown that manipulating the pre-bottleneck stage of Task 1 results in an equal effect on RT1 and RT2, while manipulating the duration of the post-bottleneck stage of either task influences that particular task alone (for reviews, see Pashler, 1994; Pashler & Johnston, 1998). The RSB model also accurately predicts the SOA effects on Task 2 performance: the shorter the interval between the onset of the two stimuli, the longer Task 2 must wait for access to the bottleneck stage. Specifically, the RSB model predicts that at very short SOAs, the slope of the RT2 curve should be -1, indicating that every millisecond that SOA is reduced corresponds to an additional millisecond that Task 2 processing must be suspended. The ability of the RSB model to explain patterns of RT1 and RT2 slowing due to the manipulation of particular discrete processing stages and SOA durations has made it one of the strongest and most favoured models of dual-task performance.

Alternative Models of Dual-Task Performance

It is important to note that the interpretation of the RT effects described above, and on which the entire RSB model is based, depends critically on the assumption that the processing stages within each task are serial and discrete, and particularly that the response selection stages of the two tasks, which form the bottleneck, proceed in a discrete and serial fashion. If this assumption did not hold, it would provide a serious challenge to the RSB model of dual-task performance.

There are other models of dual-task performance that do not depend on this discreteness assumption. For example, capacity sharing models predict that the processing for two tasks may occur in parallel, but that capacity is limited in the central stage and therefore must be shared across tasks (Navon & Miller, 2002; Tombu & Jolicœur, 2003). Capacity may be allocated in a graded fashion, and the slowing of Task 2 observed in dual-task interference is argued to be the result of the majority of processing resources being allocated to Task 1. In fact, the RSB account of dual task performance can be considered a special case of a capacity sharing model with complete capacity allocated to the first task.

Both the bottleneck and capacity sharing models are structural accounts of dual-task interference. They propose that within the stream of information processing there is a capacity-limited mechanism that can only process one task at a time, or that must share its scarce resources across two tasks. An alternative idea is that dual task interference is the result of a strategic preference for serial processing of the two tasks. Such models assume that processing for both tasks can theoretically occur fully in parallel, however since this may lead to interference at central or peripheral stages, people adopt a sequential strategy. This is the premise of Meyer and Kieras' (1997a; 1997b) executive process interactive control (EPIC) processing architecture, which relies on a strategic response deferment (SRD) model, and Logan and Gordon's (2001) executive control theory of visual attention (ECTVA). Miller, Ulrich, and Rolke (2009) also developed an optimization framework that mathematically demonstrates that serial processing is almost always more efficient than parallel processing, suggesting that serial processing is most often observed because it is optimal, rather than obligatory.

Despite the existence of numerous models that predict that the response selection processes of two tasks may proceed in parallel, the RSB model has remained the most popular model of dual-task performance likely due to its simplicity and explanatory power. The model relies on the assumption that the response selection stages for two concurrent tasks are discrete and serial, and a number of studies have been designed to provide a strong test of this assumption. According to the RSB model there should not be an influence of Task 2 response selection processing on Task 1 response selection, since the response selection stage for Task 2 cannot begin until this stage is complete for Task 1. Demonstrations of crosstalk effects on RT1 from the bottleneck stage of processing in Task 2 could suggest that these stages are active in parallel, and may therefore violate the discrete stage processing assumption on which the interpretation of evidence for the response selection bottleneck is based. This issue has been closely examined, as it has important implications for central information processing capacity and models of dual-task performance.

Investigations of Parallel Processing in Dual-Task Performance

Hommel (1998a) provided one of the first demonstrations of compatibility between Task 2 and Task 1 responses affecting Task 1 performance. In a series of experiments, participants were presented with the letter H or S in either red or green. They first had to make a manual left or right response to the colour, followed by a verbal response to the letter identity. In the first experiment, participants responded to the letter identity by saying either "right" or "left" (e.g. "right" for H, "left" for S). Response times to the first task were faster if the secondary vocal response was compatible with the manual primary response (i.e. both 'left' or both 'right'; R2-R1 compatibility). This result implies that R2 information must be available early enough to influence primary task performance. In subsequent experiments, the location-related vocal responses were replaced with colour-related vocal response to the letter identity (e.g. "red" for H, "green" for S), allowing for demonstrations of R2-S1 compatibility effects in Task 1 performance. From this set of experiments Hommel concluded that stimulus-response (S-R) translation for two tasks may be performed in parallel, and is therefore not part of the serial bottleneck stage.

The results of Hommel (1998a) differ those of Carrier and Pashler (1995), who used locus of slack logic to show that manipulations of the difficulty of episodic retrieval in Task 2 produced additive effects with SOA, indicating that retrieval of stimulus information for the Task 2 item is indeed part of the bottleneck stage, and therefore cannot occur in parallel with the bottleneck stage in Task 1. Logan and Schulkind (2000) noted this discrepancy, and decided to look for crosstalk effects from Task 2 to Task 1 using overlapping task sets (as in Hommel, 1998a) in a PRP paradigm with separate stimuli and variable SOAs (as in Carrier & Pashler, 1995). In the first experiment, participants had to judge whether the stimulus for each task was a letter or a digit. Logan and Schulkind observed category-match effects: RT1 was faster when the category of S2 matched the category of S1 (i.e. both were digits, or both were letters). This finding was replicated in three other experiments using magnitude, parity, and word/non-word discrimination tasks, as long as the same task was performed for both stimuli. When participants had to perform a magnitude judgment for Task 1 and a parity judgement for Task 2 (Experiment 2), the category match effects disappeared.

These results demonstrate that with identical task sets, participants are able to retrieve the category of both stimuli in parallel. Assuming that retrieval of stimulus information is part of the bottleneck stage, this finding violates the basic discreteness assumption of the RSB model: the bottleneck stage for Task 1 cannot be influenced by the bottleneck stage for Task 2 unless the latter commences before the former is completed. Stimulus category retrieval for each task must therefore not be a discrete, serial process. Logan and Gordon (2001) replicated these findings of parallel retrieval and extended them to picture/word judgments, while Logan and Delheimer (2001) obtained similar results using an episodic memory task: reaction times to the first stimulus were faster when both stimuli belonged to the same category (old or new), and when both were old, RT1 was faster when both items originated from the same memory structure at study (e.g., word pairs or sentences). Together, these studies support the claim that memory retrieval for two related tasks can occur in parallel.

Despite the demonstrations of crosstalk between tasks described above, the possibility remains that retrieval of stimulus category information occurs in a stage of processing prior to the bottleneck stage. If this is the case, the response selection stages of the two tasks may still be serial and discrete. A stronger claim would be that Task 1 response selection is influenced by Task 2 response information that can only be generated via Task 2 response selection processing. In all of the studies discussed previously, there existed some form of stimulus category relationship between tasks that may have produced the crosstalk effects independently of any parallel response selection. Logan and Schulkind's (2000) crosstalk effect could arise from category-level priming across tasks. For example, when both tasks involve letter/digit discrimination, categorizing S1 as a letter may be facilitated when a letter is also presented as S2, compared to when S2 is a digit. In this case the responses to both tasks are also compatible because the task set rules are identical, but it is not clear that the categorization facilitation depends on response selection processes. Even Hommel's (1998a) demonstration of R2-R1 crosstalk involved a substantial degree of conceptual overlap between tasks, with both responses defined from attributes of the same stimulus. The semantic representations of left and right for R1 and R2 may be mediated by the stimulus information itself, complicating the interpretation of the processing stage at which the crosstalk effects occurred (Watter & Logan, 2006).

Watter and Logan (2006) conducted a stronger test of the discreteness assumption in the RSB model by dissociating two sources of crosstalk: crosstalk arising from semantic stimulus category information, and crosstalk arising specifically from response information. They conducted a set of typical PRP experiments using identical or different tasks for each stimulus. The most important test of the Task 2 to Task 1 crosstalk occurred in the different task set condition. Here participants performed a magnitude judgment for Task 1 and a parity judgment for Task 2 (or vice versa), using the same or a different set of response keys (bivalent vs. univalent). With this design it is possible to independently assess both semantic and response-related crosstalk effects between tasks. For example, if a participant is presented with the digit ‘7’ in Task 1 and asked to determine if it is smaller or larger than 5, his performance on this task may be facilitated by the presence of the digit ‘9’ for Task 2, because both stimuli could be categorized as larger than 5. This would be evidence for semantic priming from Task 2 to Task 1. In addition, if the response for ‘larger than 5’ (R1) is mapped to the same key (in the case of bivalent mapping) or a compatible key (in the case of univalent mapping) as the response for ‘odd’ (R2), these two stimuli would also be response compatible. According to Watter and Logan (2006), the only way to observe a response compatibility crosstalk effect on Task 1 performance is if Task 2 is processed sufficiently to generate response information in parallel with the response selection process operating in Task 1. This would violate the discreteness assumption for the response selection stage that is central to the RSB model. Note that these two types of Task 2 to Task 1 crosstalk are completely orthogonal in this design.

Watter and Logan (2006) found clear evidence of both semantic and response crosstalk effects on Task 1 performance at short SOAs. These two effects were observed to interact in Task 1, with semantic and response compatible or semantic and response incompatible trials performed faster than trials with mixed compatibility (e.g. semantically compatible but response incompatible). This pattern of data suggests that the two effects are not entirely independent. Previous 'partial repetition' effects have been demonstrated in the task switching literature (Rogers & Monsell, 1995) and elsewhere (Hommel, 1998b, 2004; Hommel & Colzato, 2004). Importantly, the presence of response compatibility effects in Task 1 performance indicate that response information for Task 2 became available before the completion of the response selection stage in Task 1, and is therefore evidence for parallel response selection processing. This effect is now commonly referred to as the backward compatibility (or backward crosstalk) effect (BCE), because the critical effect involves priming from Task 2 response information on Task 1 performance. The BCE is interpreted as evidence for the generation of response information for two tasks at once, which is incompatible with the central assumptions of the traditional RSB model.

One boundary condition was observed by Watter and Logan (2006) in their different task set, univalent response condition, where there was no evidence of a BCE. In this condition participants responded to one task with the index or middle finger of their left hand, and the other with the same fingers of the right hand. Response compatibility was defined on the basis of finger identity (e.g. using the index finger of each hand to respond to the two tasks was considered a response compatible trial). In a second experiment they demonstrated that a BCE could be observed across hands, but required bivalent response mapping (left vs right index finger for both tasks). This result appears to suggest that some amount of overlap between tasks, in this case response keys, is necessary for response selection to proceed in parallel. This hypothesis was addressed by Miller (2006), who designed a set of experiments with unrelated tasks, having no overlap in the stimuli, S-R mapping rules, or responses used. In the first experiment, Task 1 was a simple X versus O letter discrimination performed with the middle or index finger of the left hand, and Task 2 was a go/no-go task where participants responded to either high or low tones with the index finger of their right hand, and withheld responses for the other tone. Miller observed a different form of BCE: responses to the first task were faster when Task 2 required a 'go' response than when it required a 'no-go' response. This effect was replicated in a second experiment where the task order was reversed: Task 1 was tone discrimination and Task 2 was a go/no-go task with the letter stimuli. In a final experiment, Miller demonstrated that performance in Task 1 was slower when Task 2 required a complex response (hitting a response key three times) than when it required a simple response (hitting the response key a single time). These findings indicate that even in the absence of stimulus or response overlap, Task 2 response selection begins before Task 1 response selection has completed.

Implications of the BCE for the RSB Model

The evidence for parallel response selection in the form of BCEs described above (see also Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002) poses a strong challenge to the RSB model, which relies on a strict bottleneck in the process of response selection to explain dual-task interference. Hommel (1998a) proposed the RSB model be amended to divide the traditional stage of response selection into two separate stages: a response activation stage in which S-R translation may proceed for both tasks in parallel, and a subsequent response selection stage that must be performed for each task serially. While this amended model is able to account for BCEs, it is unclear what role remains for a serially-limited response selection stage once the work of activating the appropriate response to the stimulus has been completed. It is possible that selective attention is required to bind the activated response information to the appropriate stimulus or task, and that this process occurs for each task in turn. Other models, such as graded capacity sharing or those without central capacity limitations such as ECTVA or EPIC might also be more equipped to handle BCEs than the traditional RSB model.

Before discarding the traditional RSB model, it is important to determine for certain that the BCE is in fact a demonstration of response selection for two different tasks proceeding in parallel. The work described in this thesis was designed to investigate closely the nature of the BCE: the mechanisms underlying it, how it relates to explicit response selection, and the implications it has for models of dual-task performance.

One important question concerns how the Task 2 response information producing the BCE is generated in parallel with Task 1 processing. In Hommel's (1998a) model, S-R translation can occur for two tasks automatically and in parallel during a response activation stage prior to the serial response selection stage. He proposed two mechanisms by which this might occur. In his 'transient-link' model, multiple S-R mapping rules can be active in working memory, and implemented simultaneously for automatic stimulus-response translation. In the ‘direct-link’ model, specific S-R relationships are learned episodically and form direct associations in memory such that response codes can be automatically activated for two stimuli in parallel.

A potential alternative to automatic S-R translation not considered by Hommel (1998a) is category-response (C-R) translation. In this case, response information for Task 2 is automatically activated by the semantic category representation of S2. For example, the digit 4 could activate the semantic category of ‘even digits’, and subsequently this category information would activate the response associated with that category. Automatic C-R translation may also occur via direct- or transient-links. Ellenbogen and Meiran (2008) argued in favour of a transient-link model, where the BCE results from task set rules held concurrently in working memory. They hypothesized that these rules were C-R rules, rather than specific S-R rules, and found support for this assertion by showing that the BCE was larger when the same number of stimuli were mapped to fewer categories.

It is difficult to dissociate potential mechanisms of automatic S-R or C-R translation in the existing demonstrations of the BCE in dual-task performance. Each of these studies used very small stimulus sets with no more than eight unique stimuli. Therefore even though the design may involve the mapping of categories to responses (e.g. “odd digits = left button”, “even digits = right button”), with so few stimuli repeated frequently in the experiment participants could also learn to represent specific S-R pairings (e.g. “1 = left button”, “2 = right button”). Therefore it remains unclear whether the parallel activation of response information giving rise to the BCE can occur via automatic C-R translation, independently of any influence of S-R translation.

Another relevant question is which stage of Task 1 processing is primed by crosstalk from Task 2 response information. The BCE is typically interpreted as a crosstalk effect on Task 1 response selection by response information computed simultaneously from Task 2. An alternative possibility is that it represents crosstalk from Task 2 response selection on the post-bottleneck motor stage in Task 1. This interpretation could reconcile the BCE with the traditional RSB model involving serial response selection (i.e. S-R mapping) stages. This possibility has been considered by Miller and Alderton (2006), who found that Task 2 response force requirements affected the force-time dynamics of Task 1 responses. For Task 1, participants responded with the index or middle finger of their left hand to the colour of a rectangle, and for Task 2 they were required to make either a hard or soft key press response with the index finger of their right hand based on whether S2 was an X or an O. The force of the Task 1 response was harder when Task 2 required a hard rather than soft response, showing that Task 2 processing can also affect motor output in Task 1. Miller and Alderton argued that the source of the crosstalk effect observed in their experiments was the response selection stage in Task 2 interacting with the motor execution stage in Task 1, but they could not determine for certain whether the Task 2 selection stage began before the Task 1 selection stage was complete. If this and other demonstrations of BCEs reflect priming of post-bottleneck motor stages in Task 1 without requiring that the response selection stages of the two tasks overlap, then the discreteness assumption of the RSB model remains intact.

A third important question concerns the fate of the Task 2 response information generated in parallel with Task 1 performance. Even if the response selection stage for Task 2 can proceed in parallel with attended response selection processing for Task 1, it is possible that the response information for Task 2 generated in parallel with Task 1 does not actually contribute to Task 2 performance. Once overt attention shifts from Task 1 to Task 2, any response information for Task 2 computed to that point may be discarded, and Task 2 response selection proceeds from scratch following the completion of this stage in Task 1. While this possibility does constitute a violation of the discrete stage assumption of the traditional RSB model, it still preserves the spirit of the model as the response selection stages are discrete in functional or informational terms. In this case, sufficient response information is generated for Task 2 to influence Task 1 performance, but it is either too weak or too error-prone to contribute to the computation of R2, or it is flushed from the system entirely once Task 2 becomes attended (Watter & Logan, 2006).

The concept of “flushing” is also integral to Logan and Gordon’s (2001) ECTVA. Their model begins with Bundesen’s (1990) theory of visual attention (TVA), which is controlled by an executive process that runs TVA twice in dual-task situations. The executive transmits parameters derived from the task instructions stored in working memory to the subordinate TVA, and resets its random-walk response counters to a small percentage of their previous levels between tasks in order to prevent response perseveration. Presumably, this flushing would also eliminate any response information activated for Task 2 in parallel with Task 1 performance. In ECTVA, the response counters are reset between tasks to 10% of their final value at the end of Task 1, however preserving the discreteness assumption of the RSB model would require a complete 100% flushing of activated response information between tasks (Watter & Logan, 2006). Therefore, a convincing demonstration that the BCE truly violates the discreteness assumption of the RSB would require that early, unattended Task 2 response information computed in parallel with Task 1 response selection persists across the bottleneck to contribute directly to attended Task 2 performance.

Overview of the Empirical Chapters

The goal of this dissertation is to investigate the nature of the BCE: the mechanisms underlying it, and the implications it has for parallel processing in dual-task performance. The previous section outlines three key questions about the BCE that remain to be thoroughly investigated, and each of the empirical chapters is devoted to examining one of these three issues.

In Chapter 2, I examine whether Task 2 response information can be generated via automatic C-R translation, independent of specific S-R associations. Previous demonstrations of the BCE used very small stimulus sets, leaving it unclear whether the effect is a product of automatic S-R or C-R translation that occurs in parallel with attended Task 1 processing. The chapter contains two experiments. In the first, I extend the findings of Watter and Logan (2006) to a design that includes a different set of stimuli in each task. Importantly, in the second experiment, I show evidence of a BCE when the Task 2 stimulus is unique on every single trial. The observation of a BCE in this design indicates that participants are able to retrieve the semantic category information for a stimulus and map that category information to a response, all while simultaneously engaging in effortful Task 1 response selection processing. This automatic C-R translation is discussed in terms of Hommel's (1998a) direct-link and transient-link models of S-R translation.

In Chapter 3, I examine the hypothesis that the BCE reflects priming of the response selection stage rather than the post-bottleneck motor output stage in Task 1, and simultaneously explore how the BCE changes with extended PRP practice. If the source of crosstalk producing the BCE is in fact Task 2 response selection acting on the post-bottleneck stage in Task 1, the response selection stages of the two tasks may not need to overlap, and the bottleneck would remain intact. To test this possibility, I manipulate the duration of the response selection stages of both tasks through practice, and by altering the stimulus set size for each task. If the BCE reflects crosstalk acting on Task 1 response selection, manipulating the duration of this stage should alter the magnitude of the effect. Alternatively, if the BCE reflects crosstalk at the post-bottleneck stage in Task 1, these manipulations should have little influence on the BCE.

In Chapter 4, I present a set of experiments designed to test the concept of an informational bottleneck. I use a modified PRP paradigm with a prime and target stimulus in Task 2 in order to determine if Task 2 response information generated early and in parallel with attended Task 1 response selection persists to contribute to eventual Task 2 performance. Evidence for this would constitute a clear violation of the assumption that the response selection stages for the two tasks are serial and discrete.

Finally, in Chapter 5, I briefly summarize all of these studies and highlight a number of important issues surrounding the BCE, and its implications for our capacity to perform two tasks in parallel. I also discuss the empirical results in terms of the various models of dual-task performance.

The reader should note that each of the empirical chapters were originally written as articles for journal publication, and as such are intended to stand on their own, each with a thorough introduction, description of methods and results, and discussion. Therefore the reader will notice some redundancy in the theoretical issues raised in the various empirical chapters and this general introduction. There is also considerable overlap in the description of the methodology used in the empirical chapters, as each begins with a basic PRP paradigm with modifications to the type and frequency of stimuli used. Despite the conceptual and methodological overlap, the experiments described in each chapter are unique, and designed to address distinct research questions regarding the BCE and the mechanisms underlying dual-task performance.

CHAPTER 2

Parallel Response Selection in Dual-Task Situations via Automatic Category-to-Response Translation

Thomson, S. J., Watter, S., & Finkelshtein, A. (2010).

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Abstract

In contrast to the response selection bottleneck theory of dual task performance, recent studies have demonstrated compatibility effects between secondary and primary responses on Task 1, suggesting that response information for two tasks may be generated in parallel. In two experiments, we examined the nature of Task 2 response activation in parallel with Task 1, using a PRP paradigm. Evidence of Task 2 to Task 1 response priming when each Task 2 stimulus was unique indicated that automatic parallel generation of response information occurred for Task 2 via abstract semantic category-to-response translation processes, independent of any direct stimulus-response influences. These findings are discussed in terms of their implications for the traditional response selection bottleneck theory of dual task performance.

Introduction

The psychological refractory period (PRP) paradigm (Telford, 1931) has long been used by psychologists as a tool for investigating people's ability to perform two tasks concurrently. In a typical PRP task, participants are presented with two stimuli in close temporal succession and are required to make a speeded response to each. The characteristic result in this paradigm is that the reaction time (RT) for Task 2 increases as the stimulus onset asynchrony (SOA) decreases, whereas the RT for the first task remains relatively unaffected by SOA. One common interpretation of this finding is that there exists a central processing bottleneck in the stage of response selection, such that the selection of an appropriate response to Task 2 cannot begin until this operation is complete for Task 1 (Pashler, 1984). In this sense, PRP findings demonstrate that for at least the response selection stage of processing, people are strictly unable to do two things at once.

Pashler's (1994) response selection bottleneck (RSB) theory of dual-task performance relies on the locus-of-slack logic, which assumes that tasks can be divided into processing stages that are serial and discrete. Processing stages of the two tasks in a PRP paradigm can run in parallel until the response selection stage; here, there is a bottleneck that permits this processing stage to be completed for only one task at a time. The RSB theory therefore proposes that the response selection stages of the two tasks are serial and discrete with respect to each other, and this has generally accounted well for demonstrations of the PRP effect (for reviews see Pashler, 1994; Pashler & Johnston, 1998).

Challenges to RSB Theory

More recently, several authors have taken an interest in testing this discreteness assumption. Meyer and Kieras (1997a, 1997b) proposed the executive-process interactive control (EPIC) architecture, which assumes that parallel processing is, in fact, possible in multiple-task performance and that delays in Task 2 performance at short SOAs in PRP studies are due to strategic response deferment. Tombu and Jolicoeur (2002, 2003) and Navon and Miller (2002) have argued for a central capacity sharing or divisible resource model, in which PRP effects are due to capacity-limited processes that permit graded capacity sharing across tasks, rather than a strict all-or-none bottleneck.

Cross-talk effects between tasks have also been examined. Logan and Schulkind (2000) presented four experiments demonstrating retrieval of semantic information about their Task 2 stimuli (S2) occurring in parallel with the processing of Task 1 stimuli (S1). They used a PRP paradigm with letter/digit (Experiment 1), magnitude or parity (Experiment 2), or word/nonword (Experiments 3 and 4) discrimination tasks and found that Task 1 RT was shorter when the category of S2 matched the category of S1 (e.g., both were letters) and Task 1 and Task 2 were the same. This finding suggests that participants were able to retrieve the semantic category of S2 early enough that this information was able to facilitate performance for S1. Logan and Delheimer (2001) demonstrated similar results of parallel retrieval in dual tasks involving episodic memory. Fischer, Miller, and Schubert (2007) found evidence of parallel semantic memory retrieval with non-identical tasks using locus-of-slack logic, rather than looking at cross-talk effects. They found an underadditive interaction between SOA and Task 2 semantic categorization difficulty, such that the effect was present at long SOAs but, at short SOAs, the difference was, presumably, concealed by the slack period while Task 2 waited for access to the bottleneck. If memory retrieval for S2 categorical information is assumed to be part of the process of response selection, it would appear that this stage can progress for two tasks simultaneously, violating RSB assumptions. However, it is possible that memory retrieval occurs rapidly prior to the more effortful bottleneck stage, and if this is the case, these findings do not violate the discreteness assumption of the RSB theory. In order to challenge this assumption, it would be necessary to demonstrate that actual response information for Task 2, which should not be available prior to the response selection stage, is generated in parallel with Task 1 response selection.

Hommel (1998) was successful in demonstrating that response compatibility across tasks in a dual-task situation could influence performance in the primary task. In a series of experiments, participants were presented with the letter H or S in either red or green. They first had to make a manual left or right response to the colour (R1), followed by a verbal response to the letter identity (R2). In Hommel's Experiment 1, participants responded to the letter identity by saying either "right" or "left" (e.g., "right" for H, "left" for S). Hommel found that RTs to the primary manual task were faster if the secondary task's vocal response was compatible with the primary task's manual response (e.g., left manual response, then say "left"). In subsequent experiments, Hommel also demonstrated compatibility effects between R2 and S1, suggesting that some Task 2 response information was available when S1 information was influencing R1 selection. This set of results was taken as evidence that R2 information was activated while the primary task response was being selected and led Hommel to propose that S2-R2 translation could occur automatically and in parallel with Task 1 response selection.

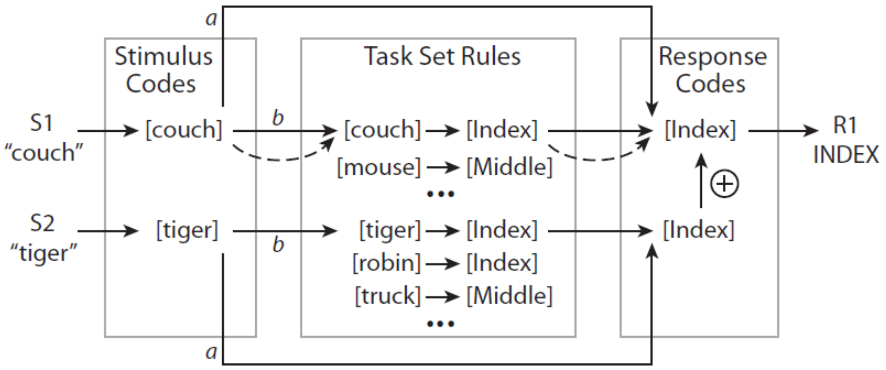
A more direct test of the RSB theory's discreteness assumption was conducted by Watter and Logan (2006), who suggested that Hommel's (1998) findings could have been due to more semantic or conceptual Task 2 to Task 1 compatibility relationships (e.g., the emphasis on the spatial codes 'left' and 'right' as both the response location for Task 1 and the verbal response for Task 2) and might not have been a particularly strong test of parallel response activation. Watter and Logan used magnitude (high/low) and parity (odd/even) tasks with single digit stimuli (1 to 9, excluding 5) in a standard PRP design, with manual response alternatives for each task mapped to the same two fingers for both tasks. Their design allowed them to dissociate the influence of S2 information on R1, generated via Task 1 relevent S2 semantic information derived under Task 1 category mapping rules (akin to a semantic flanker effect), from the potential influence of R2 information on R1. As an example, consider a participant performing a magnitude task as Task 1 presented with the stimulus "9", the correct response for which is to press a key with the index finger. A Task 2 stimulus "7" is presented at a short SOA, well before a Task 1 response has been made. In this case, S2 (7) might facilitate the categorization of S1 (9) as "high" for Task 1, as compared with an other-category alternative Task 2 stimulus of "3". This trial eventually requires a parity decision for S2 (7) as Task 2, the correct response for which will eventually also be to press a key with the index finger. In this case, while a participant is attending to and actively performing Task 1, prior to the Task 1 response and with S2 present at a short SOA, Task 1 response selection might be primed from compatible Task 2 response information, if such R2 information is being sufficiently generated in parallel with overt Task 1 response selection processes. Watter and Logan found clear evidence of separable semantic and response priming effects on Task 1 performance from Task 2 at short SOAs, suggesting that Task 2 response information was generated in parallel with attended performance of Task 1 response selection.

Miller (2006) provided further evidence of Task 2 response information's exerting an influence on Task 1 performance and extended the findings of previous authors by demonstrating this effect using unrelated tasks. For Task 2 he used a go/no-go task with either auditory (Experiment 1) or visual (Experiment 2) stimuli and found that RTs in the first task were longer when the Task 2 stimulus signaled a no-go response. Similarly, Task 1 reaction time was lengthened when Task 2 required a complex rather than simple response. Response information from Task 2 has also been shown to influence the motor output for Task 1, with Miller and Alderton (2006) demonstrating that Task 1 responses were more forceful when a hard, rather than soft, key press response was required for Task 2.

Potential Mechanisms of Parallel Response Selection

If Task 2 response information can be generated in parallel with Task 1 response selection in a standard PRP paradigm, the question then arises as to the nature of this R2 information generation. Figure 1 illustrates two general possible mechanisms: Task 2 response activation from specific stimulus representations (stimulus-to-response translation, top panel), and Task 2 response activation from task-relevant semantic

Stimulus-to-Response Translation



Category-to-Response Translation

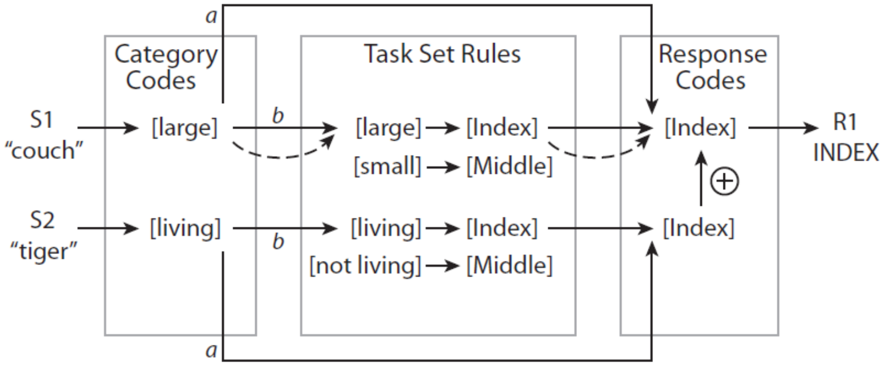


Figure 1. Possible mechanisms of Task 2 response translation in parallel with effortful Task 1 performance in a psychological refractory period (PRP) dual-task paradigm. Both panels show various routes for generating response information for both tasks, while participants are actively engaged in performing Task 1. The top panel shows relationships between specific stimulus representations and response representations (e.g., for Task 2, a stimulus "tiger" maps to an index finger response); the bottom panel shows relationships between more abstract stimulus category representations and response representations (e.g. for Task 2, a stimulus "tiger" is classified as [living] in an animacy task, and the [living] category maps to an index finger response). Dotted lines represent attended processing in Task 1, to map either a stimulus (top panel) or category (bottom panel) representation to a response representation via task set rules held online in working memory. Unattended, parallel activation of Task 2 response representations could occur via two possible mechanisms: path *a*, unattended automatic episodic retrieval of response information following association of specific stimulus-response (top panel) or category-response (bottom panel) pairs; or path *b*, unattended automatic translation via task set mapping rules held in working memory, of stimulus (top panel) or category (bottom panel) information to activate response representations. Task 2 response information generated in parallel with overt Task 1 performance might be expected to prime or interfere with response representations of Task 1.

category representations (category-to-response translation, bottom panel). The first of these possibilities is equivalent to Hommel's (1998) suggestion of automatic S-R translation. Hommel suggested two potential mechanisms to account for automatic S-R translation. In a *direct-link* model (labeled as path *a* in Figure 1), particular S-R pairs may become associated through experience, with subsequent presentations of S2 giving automatic episodic retrieval of associated R2 information, in parallel with effortful attended performance of Task 1. Hommel equated this with an instance-like account (Logan, 1988), with no need for mapping of S2 to R2 via Task 2 task set rules for this unattended process. In contrast, in a *transient-link* model (labeled as path *b* in Figure 1), stimulus-to-response mapping rules for both Task1 and Task 2 may be represented concurrently in working memory, with automatic translation of Task 2 stimuli to appropriate responses in parallel with serially-limited controlled performance via these mapping rules for Task 1. Hommel suggested that the presence of R2-R1 compatibility effects in early trials in his data, along with a the lack of clear practice effects over time, argued against an episodic direct S-R translation account, if not expressly for a transient-link account of automatic S-R translation.

A second general possibility is that Task 2 response information might be automatically activated from semantic category representations of S2, rather than from specific relationships between S2 and R2, illustrated in the lower panel of Figure 1. Such a mechanism would seem to require an additional computational step for an unattended Task 2 stimulus: S2 would need to activate the appropriate category representation with respect to the Task 2 task set rules (e.g., a stimulus "tiger" would activate a semantic category of "living" in an animacy decision task); and this category representation would need to activate the appropriate response for Task 2. Considering Hommel's (1998) distinction of direct-link versus transient-link S-R processes above, more abstract category-to-response translation might also potentially proceed via episodic learning of specific category-response (C-R) pairs (labeled as path *a* in Figure 1), or by way of automatic mapping of abstract semantic categories to responses via concurrently represented task set rules (labeled as path *b* in Figure 1).

Some evidence for a role of semantic information in automatic stimulus-response associations comes from a study by Reynvoet, Caessens, and Brysbaert (2002). They obtained response priming for parity judgments on digit stimuli with tachistoscopically presented digit primes, even for primes that were not part of the target set and were, therefore, never associated with a response. Furthermore, this priming persisted when there was no perceptual overlap between the prime and target stimuli, which strongly suggested that the S-R associations were based on the semantic features of the primes. Similarly, in their investigation of the locus of practice effects, Pashler and Baylis (1991) conducted several transfer experiments that demonstrated that novel items from a learned category benefitted from practice of items learned throughout the experiment. Their results provide evidence for the reinforcement of higher level category-to-response links that may also be detected in dual task situations.

Although the distinction between episodic accounts of S-R versus C-R response activation seems clear (the same memory processes would be involved, with either specific stimuli or specific category representations acting as retrieval cues), conceptions of automatic category-to-response versus stimulus-to-response translation via working-memory-mediated task-mapping rules may be less distinct. One might generally consider that the mapping of specific stimuli to responses in many situations is achieved via task set rules that map task-salient stimulus features to appropriate response representations; in this situation, mapping of a common feature shared across stimuli to a response might be considered as mapping via a category-like rule, even when these features are primarily perceptual. However, although we might design and describe an experimental task by way of category mapping rules, a number of different rule representations might actually be used by participants after some experience in performing a task. For example, with a limited number of repeated stimuli, the set of specific S-R mappings for a given task might become individually represented (e.g., for a parity task, 1 = right hand, 2 = left hand, 3 = right hand, etc.), instead of or in addition to a C-R mapping rule (e.g., odd = right hand, even = left hand). In some circumstances, such as with one-to-one mapping of stimuli and responses (as in Hommel, 1998), these relationships would seem to be equivalent, although one might still make a distinction between representations of a specific stimulus versus that stimulus's potential task-relevant category.

The Present Study: Testing Parallel Category-to-Response Translation

In considering these potential mechanisms, it appears that there has been no good test of category-to-response translation in mediating Task 2 to Task 1 response-priming effects. Previous work by Hommel (1998), Miller (2006), and Miller and Alderton (2006) studied these effects with simple S-R mapping tasks in which small sets of stimuli were repeated frequently throughout experiments and did not meaningfully consider potential category-to-response mechanisms. Although Watter and Logan (2006) described the response generation processes for both tasks in terms of stimulus-to-category and then category-to-response activations and empirically distinguished semantic category- from response-related Task 2 to Task 1 priming effects, two issues prevent meaningful conclusions about potential category-to-response mechanisms. First, frequent stimulus repetition within each task could have led to the development of automatic S-R translation processes (either episodic or via specific S-R rules) independent of mediation via more abstract categories. Second, the use of the same stimuli for Task 1 and Task 2, although orthogonally mapped to different tasks, still resulted in a subset of stimuli being consistently mapped to the same response for both Task 1 and Task 2. (For example, if a magnitude Task 1 mapped high stimuli to the index finger and a parity Task 2 mapped odd stimuli to the index finger, the stimulus "9" would always require an index finger response for both Task 1 and Task 2, despite different task mapping rules.) If the immediate S-R relationships (either episodic or rule-based) for these consistently-mapped stimuli were more strongly learned or represented than for other continually-remapped stimuli, this could represent a different potential source of Task 1 response facilitation effects: Although S-R translation for S2 might still occur in parallel with Task 1 response selection, the development of these S-R relationships could occur substantially through experience in Task 1, diluting Watter and Logan's claims about the parallel operation of Task 2 response generation processes.

The goal of the present study was to examine the nature of Task 2 response activation processes occurring in parallel with Task 1 in dual-task situations. As a first step, we sought to more stringently determine whether R2-to-R1 priming could be observed when reliable R2 information could only be generated from stimuli presented exclusively in Task 2. Experiment 1 replicated the cross-task priming PRP design of Watter and Logan (2006) using stimuli that did not overlap between tasks, where response information derived for S2 could only be the result of mapping that stimulus to a response using the Task 2 task set mapping rules.

As a more direct test of specific stimulus-to-response versus category-mediated translation accounts of parallel response activation, Experiment 2 examined whether Task 2 response information could be generated only from semantic category information in parallel with Task 1 response selection, in the absence of any potential direct S-R episodic or specific S-R rule-based translation effects for Task 2. To achieve this, we presented a unique stimulus for S2 on every trial, in addition to having no stimulus overlap between tasks. Task 2 to Task 1 response-priming effects in this situation cannot be attributed to any kind of direct or specific S-R translation, as each S2 stimulus is presented only once; instead, this would be evidence for automatic activation of R2 information from more abstract semantic category information, in parallel with attended performance of Task 1 response selection.

Experiment 1

In Experiment 1, participants performed a typical PRP task using word stimuli. Task 1 was a size discrimination task; participants were to determine if a given noun (S1) represented something that was larger or smaller than a computer monitor. For Task 2, they were to judge whether or not S2 represented something that was living or nonliving.

The stimulus set for each task consisted of a small number of nouns unique to each task that were repeated within task throughout the experiment.

Method

Participants. Thirty-one undergraduate students from McMaster University (23 females) participated in the experiment in exchange for partial course credit. All participants had normal or corrected-to-normal vision, and 28 were right-handed.

Apparatus and Stimuli. The stimuli were 16 five-letter nouns, presented in white on a black background using a ViewSonic Professional series P95f+ monitor that was controlled by a Dell Dimension 4600 computer. Two stimuli were presented on each trial, one above the other in the center of the screen. The participants were seated at a viewing distance of approximately 50 cm, and from this distance, each word stimulus subtended approximately 1º of visual angle in height and 3.5º in width. The vertical separation between the near edges of the two stimuli was approximately 1.5º. The two stimuli were separated in time by an SOA of 0, 200, or 800 msec, and the participants made a response to each stimulus by pressing the “1” or “2” button on the number pad of a standard computer keyboard with either the index or middle finger of the right hand, respectively.

The participants performed a separate task for each stimulus. As Task 1, they were required to identify whether the top stimulus word (S1) represented a large thing or a small thing (size task). “Large” items were described as being larger than the computer monitor, and “small” items were those smaller than the computer monitor. For Task 2 they judged whether the bottom stimulus word (S2) was alive or not (animacy task). All the stimuli for both Task 1 and Task 2 were unambiguously classifiable under both size and animacy task rules. Importantly, the same eight of our total 16 words were always presented only in Task 1, and the other eight words were always presented only in Task 2. There were an equal number of items in each task category (large vs. small, living vs. nonliving), and these were divided evenly across tasks such that there were two words from each of the four dual-category combinations (large/living, large/nonliving, small/living, small/nonliving) in the stimulus set for each task. A one-way ANOVA conducted on the Kučera and Francis (1967) written word frequencies for our stimuli revealed no significant differences among categories [$F(3,12) = 0.70$, $MS_e = 59.15$, $p = .57$].

Procedure. The experiment consisted of 512 trials, made up of eight iterations of the factorial combination of the eight stimuli for Task 1 and the eight stimuli for Task 2, with SOA randomly determined for each trial. Trials were presented in randomized order in 16 blocks of 32 trials each, and participants were given the opportunity to rest before initiating the beginning of each block. Prior to the experimental trials, the participants completed a practice block of 16 trials that were not included in the analysis. On every trial, a fixation screen was first presented for 500 msec. This display consisted of two rows of two dashes centered on the screen, separated laterally by approximately 5° of visual angle within each row, flanking the locations where S1 and S2 would appear. On 0-msec SOA trials, this display was replaced with a display of S1 and S2 for 1,000 msec, followed by a blank screen for 2,000 msec. Otherwise, the fixation screen was replaced with S1 alone, with S2 accompanying it after the SOA duration. Both stimuli were presented together for 1,000 msec, followed by a blank screen for 2,000 msec. Response mapping for each task was counterbalanced between participants across the index and middle finger of the right hand.

The participants were told that the experiment was a test of their concentration, to see how quickly and accurately they could perform successive simple tasks. They were told that the size task (Task 1) was most important and was always to be completed first, and it was explicitly stated that they should not wait until the second stimulus appeared before responding to S1. They were instructed to respond as quickly and as accurately as they could to the first (top) stimulus, and that only once they had completed their response to this task were they to turn their attention to performing the animacy task. A card attached to the bottom of the computer display served to remind the participants of the response mapping for the tasks. At the end of every block participants were informed of their average accuracy and RT for Task 1.

Data Analysis. Mean RTs were computed for trials in which both Task 1 and Task 2 were correct. Trials with RTs less than 200 msec were excluded from analysis, as well as trials with Task 1 RTs over 2,000 msec or Task 2 RTs over 2,500 msec. The data analysis aimed to determine the potential semantic- and response-priming effects of each task on the other. For Task 1, on each trial, we assessed whether S2 was of the same or a different category as S1 with respect to the Task 1 task set rules (i.e., large or small)—a category-level compatibility relationship akin to a semantic flanker effect—and whether the response to Task 2 (R2) was the same or different as the response to Task 1 (R1). For Task 2, we evaluated the same relationships, now with S1 and S2 compatibility based on their classification under Task 2 task set rules (i.e., living or nonliving), plus the compatibility of R1 and R2. Note that the semantic compatibility relationships may differ between tasks on a single trial (S1 and S2 may be compatible under the Task 1 rules, but not according to the Task 2 rules, and vice versa), but response compatibility is necessarily consistent across tasks on a given trial. Task 1 and Task 2 semantic and response compatibility relationships were evaluated across all SOAs. Mean RTs for Task 1 and Task 2 were submitted to separate 2 (semantic compatibility) x 2 (response compatibility) x 3 (SOA) repeated measures ANOVAs, with all variables treated as within-subjects factors.

Although participants were instructed to give priority to completing Task 1 prior to performing Task 2, it is possible that, on at least some trials, the participants may have withheld responding and considered their responses to both tasks prior to making their response to Task 1. In this situation, priming of a Task 1 response from Task 2 response information would not require any degree of parallel response activation. To test for this possibility, we examined mean Task 1 RTs for our shorter SOA conditions (0 and 200 msec) separated by interresponse interval (IRI) quintile. Separate 2 (semantic compatibility) x 2 (response compatibility) x 5 (IRI) repeated measures ANOVAs were conducted, with all variables treated as within-subjects factors.

Error rate data represent participants' combined performance on both tasks. Errors were coded according to the Task 1 categories of semantic and response compatibility for each trial, given our primary focus on Task 1 performance under the influence of Task 2 information. Coding errors according to the Task 2 conditions reallocates half of the trials in the semantic categories but does not affect the response classification, since response compatibility is consistent across tasks. Evaluating accuracy on the basis of the Task 2 conditions did not alter our results, so we report only the accuracy data coded via Task 1 conditions here. The participants' combined error rate data were submitted to three-way repeated measures ANOVAs identical to those used for primary RT analyses.

Results

Data from five participants were excluded from analysis due to overall error rates of greater than 30%. An additional participant was excluded for having overall RTs that were more than three standard deviations longer than the average for the participant group. RT trimming for the remaining 25 participants removed an average of 2.9% of the trials from each participant's data set.

Mean RTs for trials on which responses to both tasks were correct are presented for Task 1 and Task 2 in Figure 2. A PRP effect was observed, with RTs decreasing with increasing SOA in Task 2; Task 1 RTs were relatively flat across SOAs, although some speeding of RT with longer SOA was also observed here. For Task 1, response compatibility effects were apparent at 0- and 200-msec SOAs, with response-compatible trials faster than response-incompatible trials, although this effect appeared less distinct at the 800-msec SOA. These observations were supported by a main effect of response compatibility [$F(1,24) = 7.54$, $MS_e = 2160.94$, $p < .05$]. The pattern of response compatibility relationships appeared to interact with semantic compatibility, although this effect was marginal [$F(1,24) = 3.92$, $MS_e = 3674.89$, $p = .059$]. There was no main effect of semantic compatibility, nor other interactions involving this factor. Observed variability in overall RT across SOAs also produced a significant main effect of SOA [$F(2,48) = 4.36$, $MS_e = 19740.83$, $p < .05$].

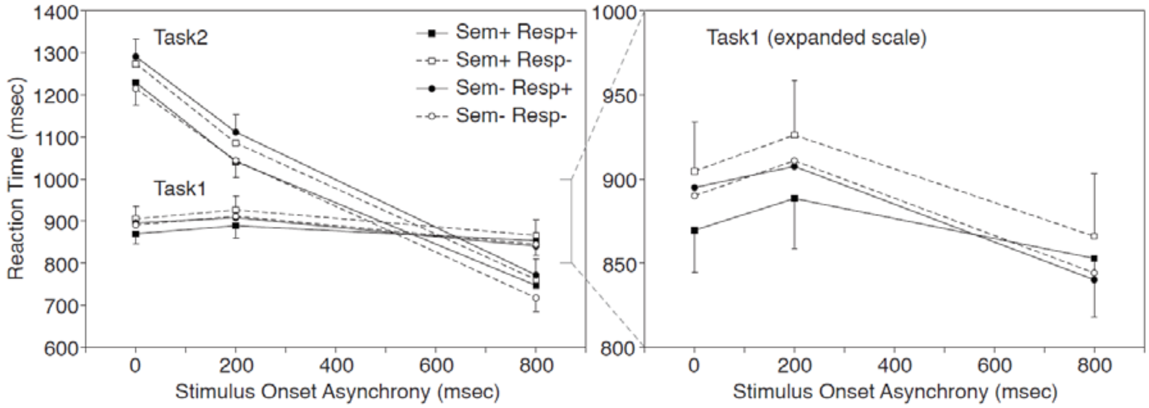


Figure 2. Reaction time (RT) data for Experiment 1. The left panel shows mean RT data for Task 1 and Task 2, and Task 1 data are presented at a larger scale in the right panel. Data are separated by combinations of semantic-compatible (Sem+) and -incompatible (Sem-) and response-compatible (Resp+) and -incompatible (Resp-) conditions. Error bars represent standard errors and are representative of the standard errors in all the conditions within a given task. Critical Task 2 to Task 1 response compatibility effects are demonstrated in Task 1 data, with response-compatible trials (Resp+, solid lines) faster than response-incompatible trials (Resp-, dashed lines), most evident at 0- and 200-msec stimulus onset asynchronies.

Similar results were observed for Task 2. An expected strong main effect of SOA was observed [$F(2,48) = 807.93$, $MS_e = 8026.45$, $p < .001$]. In addition to a main effect of response compatibility [$F(1,24) = 4.43$, $MS_e = 4329.26$, $p < .05$], the interaction between response compatibility and semantic compatibility was also significant [$F(1,24) = 35.62$, $MS_e = 5322.77$, $p < .001$], reflecting faster performance for all-compatible (semantic- and response-compatible) and all-incompatible (semantic- and response-incompatible) trials, as compared with mixed-compatibility trials across SOAs.

Mean RT data for Task 1, separated by IRI quintile, are presented in Figure 3. There was little evidence of Task 1 response compatibility effects being due to withholding of Task 1 responses while Task 2 responses were considered. The response compatibility effect, and interactions of response and semantic compatibility were observed across IRI quintiles, with little overall RT difference observed across quintiles. At the 0-msec SOA, these observations were supported by significant interactions of semantic and response compatibility [$F(1,24) = 4.59$, $MS_e = 10474.16$, $p < .05$] and of response compatibility and IRI quintile [$F(4,96) = 2.49$, $MS_e = 8755.67$, $p < .05$], both modifying a marginal main effect of response compatibility [$F(1,24) = 2.96$, $MS_e = 8619.90$, $p = .099$]. At the 200-msec SOA, there was a main effect of response compatibility [$F(1,24) = 10.28$, $MS_e = 5139.60$, $p < .01$], with an interaction of semantic compatibility and IRI quintile [$F(4, 96) = 2.89$, $MS_e = 10010.36$, $p < .05$], modifying a marginal main effect of IRI quintile [$F(4,96) = 2.01$, $MS_e = 22599.54$, $p = .099$].

Mean combined Task 1 and Task 2 error rate data are summarized in Table 1. Although error rates were determined on a trial-wide basis including both tasks, more than 75% of errors were observed to arise from overt performance of Task 2. In general, accuracy of performance was consistent with the RT data. Main effects of response compatibility [$F(1,24) = 17.70$, $MS_e = 0.001$, $p < .001$] and semantic compatibility [$F(1,24) = 17.26$, $MS_e = 0.008$, $p < .001$] were modified by an interaction between these two factors [$F(1,24) = 24.99$, $MS_e = 0.011$, $p < .001$]. All-compatible and all-incompatible trials were more accurate than mixed-compatibility trials across SOAs. Accuracy also increased with SOA, as demonstrated by a main effect of SOA [$F(2,48) = 3.29$, $MS_e = 0.004$, $p < .05$].

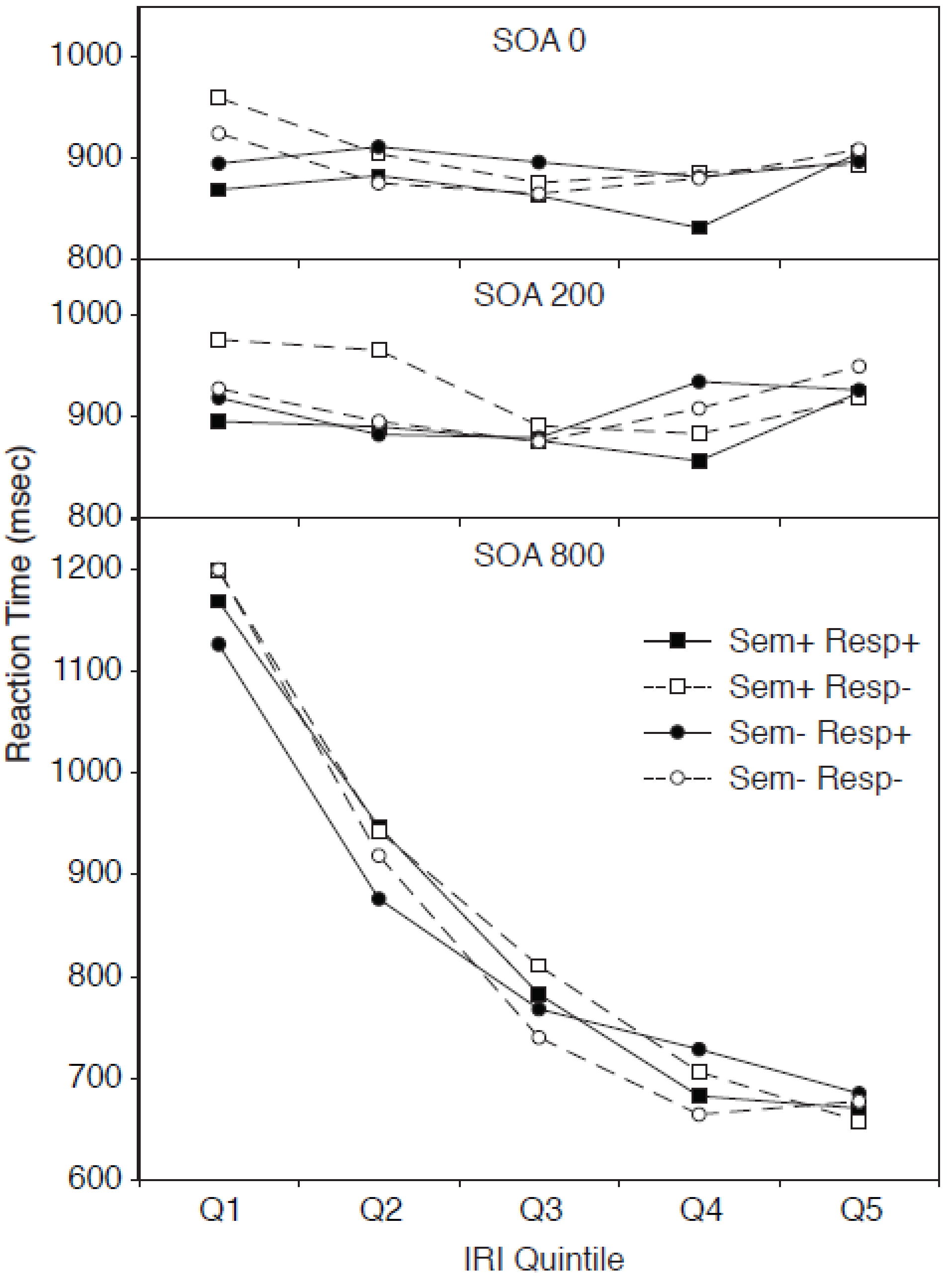


Figure 3. Task 1 reaction time (RT) data for Experiment 1, separated by interresponse interval (IRI) quintile. Mean RT is plotted over IRI quintiles for each stimulus onset asynchrony (SOA) separately, for combinations of semantic-compatible (Sem+) and -incompatible (Sem-) and response-compatible (Resp+) and -incompatible (Resp-) conditions. At shorter SOAs (0 and 200 msec), RTs for response-compatible conditions at smaller IRI quintiles were equivalent to or faster than RTs at larger IRI quintiles, suggesting that critical Task 2 to Task 1 response compatibility effects were not due to strategic delaying or grouping of Task 1 responses.

Table 1. Mean dual-task error rates (% Error) and standard errors of the mean (SEM) for Experiment 1 and Experiment 2.

	Sem+				Sem-			
	Resp+		Resp-		Resp+		Resp-	
SOA	% Error	SEM	% Error	SEM	% Error	SEM	% Error	SEM
				Experiment 1				
0	7.60	0.02	9.41	0.02	14.83	0.03	4.28	0.01
200	5.56	0.02	7.69	0.01	14.38	0.02	3.44	0.01
800	5.03	0.01	6.66	0.01	12.85	0.02	2.82	0.01
				Experiment 2				
0	14.92	0.02	11.21	0.01	18.69	0.02	6.54	0.01
200	11.77	0.01	8.78	0.01	15.79	0.02	7.97	0.01
800	10.36	0.01	7.98	0.01	14.90	0.02	5.74	0.01

Note—Data are divided by semantic-compatible (Sem+) or -incompatible (Sem-) and response-compatible (Resp+) or -incompatibile (Resp-) trials and by stimulus onset asynchrony (SOA). Error rates reflect errors on either Task 1 or Task 2 of a particular trial; most errors were committed on overt Task 2 performance.

Discussion

Task 1 to Task 2 priming was expected and unsurprising here, since explicit Task 2 performance was deliberately constrained to follow Task 1 performance in series. Our primary focus was on whether Task 2 response information was being generated early enough and in parallel with overt Task 1 performance to influence Task 1 response selection. The results from Experiment 1 replicated those of Watter and Logan (2006), who demonstrated the influence of Task 2 response information on Task 1 responses at early SOAs. Importantly, our present data replicated their findings using separate stimulus sets for each task, suggesting that this critical R2-to-R1 priming effect is not driven by stimuli with identical S-R mappings across tasks. These findings support the notion that Task 2 response information can be generated from S2 in parallel with overt performance of Task1 response selection and that this can occur when S2-R2 relationships can be derived only under Task 2 task set rules.

Analysis of Task 1 RT over IRI quintiles did not support the possibility that the Task 1 response compatibility effects were due to delaying or withholding of Task 1 responses. Mean RTs for response-compatible trials at smaller IRI quintiles were observed to be equivalent to or shorter than RTs at larger IRI quintiles, with response-incompatible trials at earlier quintiles markedly slower. If our Task 1 compatibility effects were due to delaying of Task 1 responding and grouping of Task 1 and Task 2 responses, one would expect to observe response compatibility effects at short IRIs with a marked increase in overall Task 1 RT, relative to trials at longer IRIs. We observed no evidence of such Task 1 delaying or response grouping in this experiment, strengthening our claims of parallel response activation.

Although error rates were somewhat higher than in some more traditional PRP studies, they were extremely comparable to those in other PRP studies, such as Watter and Logan (2006), using stimuli and tasks with similarly high degrees of potential cross-task priming and interference. Errors were much more frequently observed in mixed-compatibility conditions, with a large majority of these committed on overt Task 2 performance. This pattern of data suggests that participants were focusing on Task 1 and achieving relatively accurate overall Task 1 performance, with interference arising from semantic and response compatibility relationships plus the overt Task 1 response manifesting as more errorful responses on Task 2.

What is not clear from this experiment is whether this unattended parallel S2-to-R2 generation process is a result of learning and subsequent automatic retrieval of particular S-R pairs from a given S2 (akin to Hommel's [1998] direct-link model of automatic S-R translation), whether R2 is being automatically generated via specific S-R mapping rules in working memory (akin to Hommel's [1998] transient-link model of automatic S-R translation), or whether more abstract category-to-response versions of these episodic or rule-based mechanisms might be involved. Since there were only eight Task 2 stimuli in this experiment, the participants encountered each S2 word 64 times over the experimental session. It would not be surprising if the participants were capable of learning specific S-R associations for each Task 2 stimulus within the course of this experiment (as in Watter and Logan, 2006), with unattended retrieval and activation of R2 directly from S2 in parallel with overt Task 1 performance; similarly, this situation could be conducive to developing specific S-R mapping rules.

It would be potentially more interesting if participants could generate R2 information from S2 in parallel with Task 1 response selection without any influence of previously acquired S-R learning or specific S-R task rule development for Task 2. Such a finding would suggest that Task 2 response information was being generated from semantic category information from S2—possibly as a more abstract episodic form of automatic translation of C-R associations, or as an unattended implementation of category-to-response mapping rules.

Experiment 2

Experiment 2 explicitly examined whether Task 2 response information could be generated from S2 in the absence of any previously experienced S-R pairs. We employed a very large Task 2 stimulus set, again separate from Task 1 stimuli as in Experiment 1, with the same strict cross-task semantic- and response-priming PRP method. Participants encountered each S2 only once throughout the experiment. As such, any Task 2 to Task 1 response priming observed must be due to participants' ability to activate R2 information from the semantic category of a unique S2 stimulus, in parallel with overt performance of Task 1. Such a finding would go beyond prior S-R accounts (e.g., Hommel, 1998) and would suggest that parallel automatic response activation is substantially mediated via semantic category representations.

Method

Participants. Forty-eight undergraduate students (26 females) participated in the experiment in exchange for partial course credit. All the participants had normal or corrected-to-normal vision, and 33 were right handed.

Apparatus and Stimuli. The computer apparatus and tasks performed by the participants were the same as those in Experiment 1. The stimuli were 240 nouns, which included the 16 words making up the stimulus set for the previous experiment. The same 8 words were used for Task 1, and the stimulus set for Task 2 was made up of the remaining 232 words. Again, all the words were distinctly classifiable under the task set rules for each task. There were an equal number of words in each task set category (large/small, living/nonliving), as well as an equal number of dual-category combinations in both Task1 and Task 2. Two separate one-way ANOVAs revealed no significant differences in word length [$F(3,236) = 1.56$, $MS_e = 3.91$, $p = .20$] or Kučera and Francis (1967) written word frequency among categories [$F(3,236) = 2.20$, $MS_e = 437.18$, $p = .09$].

Procedure. The experiment consisted of 232 trials, divided into 7 blocks of 30 trials and a final block of 22. Each Task 2 item was presented only once and in random order; the eight Task 1 stimuli were iterated 29 times to create a complete stimulus set, and then presented in random order over the 232 trials. Before the experiment began, the participants were informed of the two tasks and completed a practice block of 24 trials. The Task 1 stimuli for the practice block were the same as those used throughout the experiment, and the stimuli for Task 2 were an additional 24 unique words not used in the experimental trials. All other aspects of stimulus presentation and response mapping were identical to those in Experiment 1. The priority of Task 1, as well as strict serial performance of the two tasks, was again emphasized to the participants at length. RT and error rate data were analyzed as in Experiment 1.

Results

Mean RTs were computed for trials in which both Task 1 and Task 2 were correct. Data from 7 participants were excluded from analysis due to overall error rates of more than 30%. Data from an additional participant were excluded because of RTs that were more than three standard deviations longer than the average for the group. RT trimming removed an average of 2.4% of trials from each of the remaining 40 participants.

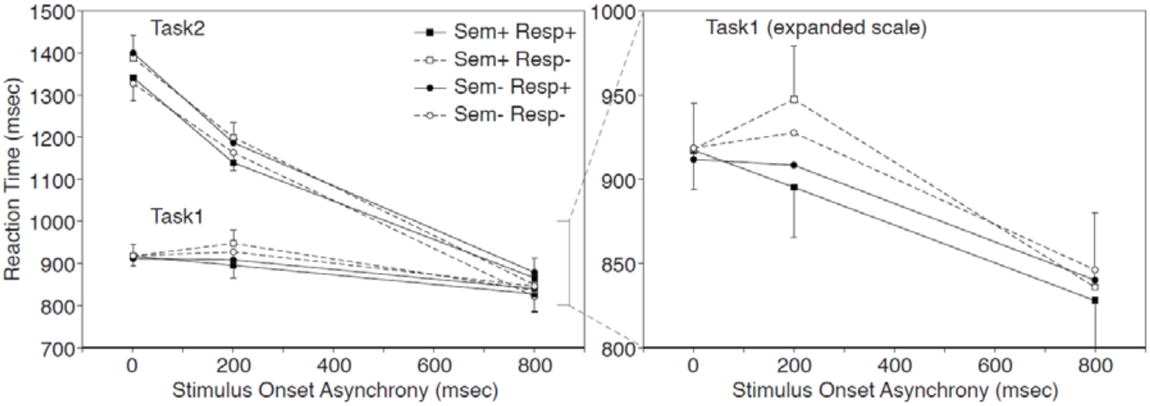


Figure 4. Reaction time (RT) data for Experiment 2. The left panel shows mean RT data for Task 1 and Task 2, and Task 1 data are presented at a larger scale in the right panel. Data are separated by combinations of semantic-compatible (Sem+) and -incompatible (Sem-) and response-compatible (Resp+) and -incompatible (Resp-) conditions. Error bars represent standard errors and are representative of the standard errors in all conditions within a given task. Critical Task 2 to Task 1 response compatibility effects are demonstrated in Task 1 data, with response-compatible trials (Resp+, solid lines) faster than response-incompatible trials (Resp-, dashed lines), most evident at 200-msec stimulus onset asynchrony.

Mean RT data for Task 1 and Task 2 are presented in Figure 4. Once again, a PRP effect was observed, with RTs decreasing with increasing SOA in Task 2; Task 1 RTs were relatively flat across SOAs, although some speeding of RT with longer SOA was also observed here. For Task 1, response compatibility effects were clearly observed at the 200-msec SOA, with response-compatible trials faster than response-incompatible trials. This pattern appeared to be numerically present at the 0- and 800-msec SOAs but was much less distinct. These observations were confirmed by a significant main effect of response compatibility [$F(1,39) = 9.92$, $MS_e = 4598.74$, $p < .01$], with a significant interaction of response compatibility with SOA [$F(2,78) = 3.17$, $MS_e = 3763.96$, $p < .05$]. The main effect of SOA was significant [$F(2,78) = 14.36$, $MS_e = 31505.34$, $p < .001$, with no significant main effect or interactions of semantic compatibility (Fs < 1).

Task 2 RT data revealed an expected strong main effect of SOA [*F*(2,78) = 917.22, MS_e = 11795.59, *p* < .001]. Evidence of both semantic and response compatibility relationships was observed. As in Experiment 1, all-compatible and all-incompatible trials were faster than trials with mixed semantic and response compatibility, supported by interactions of semantic and response compatibility [*F*(1,39) = 33.89, MS_e = 7081.21, *p* < .001], and of response compatibility and SOA [*F*(2,78) = 5.49, MS_e = 5880.60, *p* < 001], with a marginal 3-way interaction [*F*(2,78) = 2.63, MS_e = 5214.51, *p* = .079].

Mean RT data for Task 1, separated by IRI quintile, are presented in Figure 5. Mean RTs appeared to vary systematically with IRI, with an approximate 100-msec increase in mean RT over the longest to shortest IRI quintiles for most conditions at the 0- and 200-msec SOAs. Task 1 compatibility effects were not limited to short IRI quintiles: For the 0-msec SOA, patterns of semantic and response compatibility effects were most evident at the third and fourth IRI quintile; for the 200-msec SOA, a strong response compatibility effect was present over all quintiles. These observations were supported at the 0-msec SOA by a main effect of IRI quintile [*F*(4,152) = 7.49, MS_e = 20,855.83, *p* < .001], and a significant 3-way interaction of semantic compatibility, response compatibility, and IRI quintile [*F*(4,152) = 2.63, MS_e = 18,224.25, *p* < .05]. At the 200-msec SOA, there was a main effect of IRI quintile [*F*(4,152) = 9.15, MS_e = 27,706.97, *p* < 0.001, and a main effect of response compatibility [*F*(1,38) = 18.09, MS_e = 20,020.11, *p* < .001. There was no interaction of response compatibility and IRI quintile [*F*(4,152) = 0.28], and no other effects or interactions, (all *F*s < 1.5).

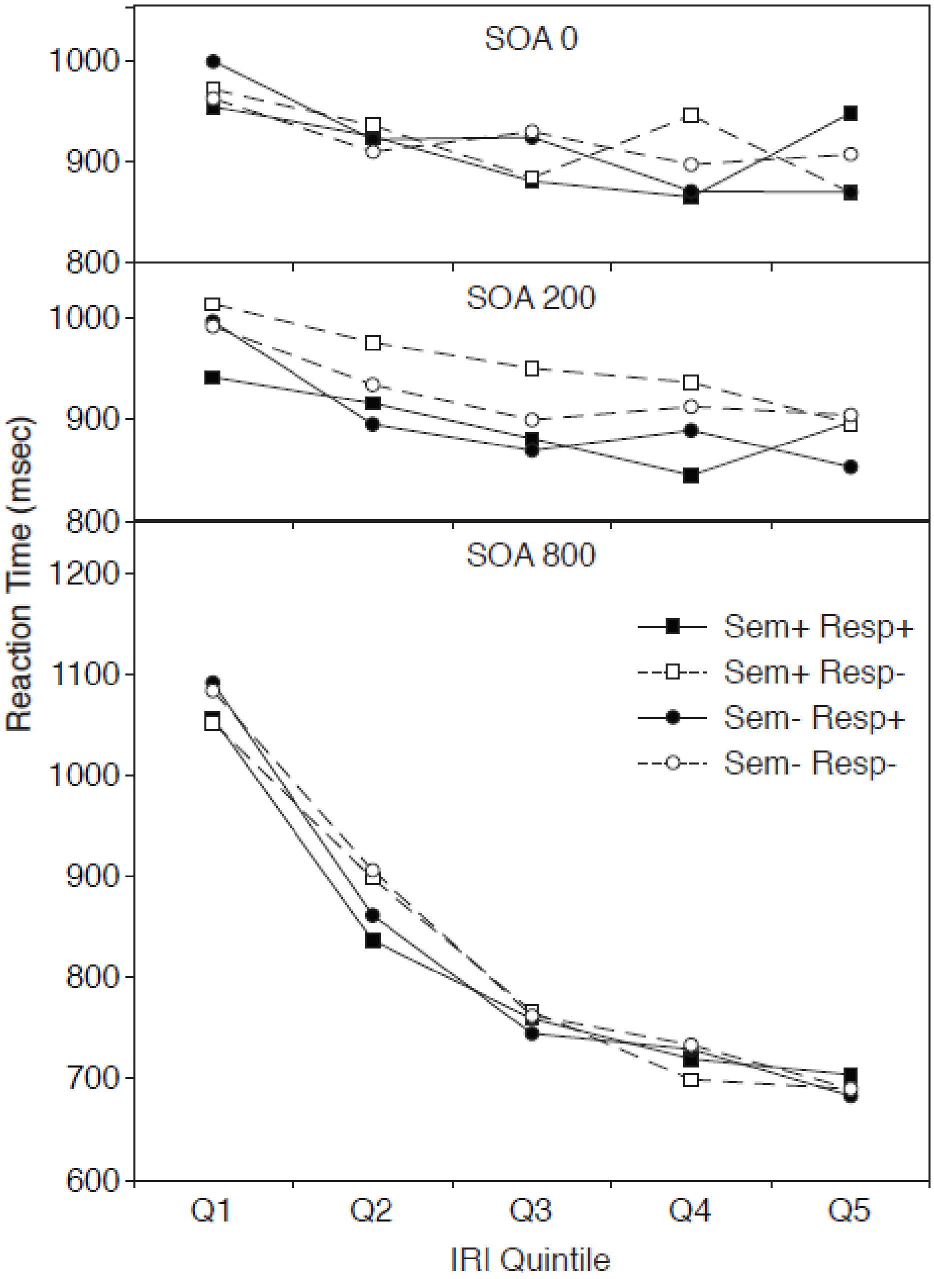


Figure 5. Task 1 reaction time (RT) data for Experiment 2, separated by interresponse interval (IRI) quintile. Mean RT is plotted over IRI quintiles for each stimulus onset asynchrony (SOA) separately, for combinations of semantic-compatible (Sem+) and -incompatible (Sem-) and response-compatible (Resp+) and -incompatible (Resp-) conditions. Critical Task 2 to Task1 response compatibility effects at 200-msec SOA were observed across all IRI quintiles, with overall RTs comparable to those in Experiment 1, suggesting that these effects were not due to strategic delaying or grouping of Task 1 responses.

Error rate data representing the combined errors for both tasks are displayed in Table 1. These data were once again coded according to the Task 1 categories of semantic and response compatibility. As in Experiment 1, although errors on either task excluded a whole trial as errorful, more than 70% of errors were observed to arise from overt performance of Task 2. Analysis revealed a main effect of response compatibility [$F(1,39) = 30.93$, $MS_e = 0.016$, $p < .001$], with response-compatible trials less accurate, overall, than response incompatible trials. This effect was modified by an interaction with semantic compatibility [$F(1,39) = 15.75$, $MS_e = 0.008$, $p < .01$], indicating that for a given level of response compatibility, the participants were less errorful when semantic compatibility was similarly compatible or incompatible, as compared with mixed-compatibility conditions. Consistent with Experiment 1, accuracy also improved across SOA [$F(2,78) = 8.01$, $MS_e = 0.005$, $p < .01$].

Discussion

The purpose of Experiment 2 was to investigate whether the Task 2 to Task 1 response priming effects observed in Experiment 1 and in Watter and Logan (2006)—and perhaps also in other studies (e.g., Hommel, 1998; Miller, 2006; Miller and Alderton, 2006)—were caused solely by effects of specific S-R associations (either episodic or task set-mediated) for Task 2 stimuli, or whether R2 information might be generated in parallel via more abstract category-to-response processes. In Experiment 2, the participants were presented with a novel S2 on every trial, which eliminated any opportunity for direct S-R episodic or specific S-R mapping effects for Task 2. In our RT data, Task 2 to Task 1 response-priming effects were still evident, as demonstrated by faster performance in Task 1 on response-compatible trials than on response-incompatible trials, primarily at the 200-msec SOA. Analysis of Task 1 RT data over IRI quintiles again suggested that our findings of response priming from Task 2 to Task 1 were not the result of participants' withholding their response to Task 1 until they had calculated a response to Task 2, with the primary R2-to-R1 compatibility effects at the 200-msec SOA observed consistently across all IRI quintiles, with mean RTs comparable to Experiment 1. Overall, our RT data suggest that the participants were able to extract semantic information regarding the animacy of a novel S2 and have the resulting category representation (living or nonliving) activate the appropriate Task 2 response, while they were simultaneously engaged in actively performing Task 1 response selection.

Although our error results suggested a different pattern of interaction between semantic and response compatibility than in Experiment 1, these data were composed mostly of errors committed on Task 2, and, as such, likely reflect cross-task priming and interference from Task 1 information on Task 2 performance with novel stimuli. The slightly higher observed error rate for Experiment 2 may reflect the additional difficulty of responding to all novel Task 2 stimuli; this said, these error rates are comparable to those observed by Watter and Logan (2006) using PRP designs with similarly high degrees of semantic and response overlap between tasks.

Several possible mechanisms might be considered for the parallel generation of Task 2 response information from S2 semantic information. One possibility is that category-to-response relationships in Task 2 could be learned and, subsequently, automatically recalled in parallel with overt Task 1 response selection, akin to the specific stimulus-to-response learning suggested by Hommel (1998) as the basis of his direct-link translation model of parallel response activation, comparable to an instance-like account (e.g. Logan, 1988). In this case, stimulus category representations (for example, living or nonliving in our present Task 2) would need to become sufficiently and consistently activated from a succession of unique S2 stimuli, so that particular C-R pairings could be encoded sufficiently well. Subsequent presentations of new S2 stimuli would need to generate appropriate and sufficient semantic category representations, which could act as retrieval cues for associated response information. The retrieval mechanism here is no different from the episodic description offered by Hommel for his direct-link account of automatic S-R translation. Our present situation would require the additional abstraction of semantic category information from individual stimuli and the learning of an association of this more abstract representation and a response, and would require that this more abstract representation be able to be activated and then act as a retrieval cue from a succession of novel stimuli, all while participants are effortfully attending to and performing a different, separate task.

An alternative to this account is consistent with a more comprehensive version of Hommel’s (1998) transient-link model, where task sets of both tasks are maintained in working memory, with unattended and automatic stimulus to response translation via these mapping rules in parallel with controlled Task 1 performance. Importantly, task set representations would have to allow translation of response information from abstract semantic category representations, without any need for direct or specific S-R mediation.

This kind of account could be more fully aligned with alternative models of dual-task performance, such as Navon and Miller's (2002) resource model, Tombu and Jolicoeur's (2002, 2003) central capacity sharing model, Meyer and Keiras' (1997a, 199b) strategic response deferment model, or Logan and Gordon's (2001) executive control of theory of visual attention model, all of which allow true parallel computation of responses for two concurrent tasks to some degree. All of these possibilities, including an automatic category-to-response (C-R) adaptation of Hommel's episodic direct-link model, have potential implications for the traditional RSB model and for our conception of *response selection* in general and are considered further in the General Discussion section below.

Although Experiment 2 most importantly demonstrated the critical effect of Task 2 to Task 1 response compatibility, several differences were noted, as compared with the data from Experiment 1. Although semantic compatibility effects from S1 were observed in Task 2 RTs, no semantic compatibility effects of S2 were observed on Task 1 performance in Experiment 2. In our Experiment 1 and in Watter and Logan (2006), this S2-to-R1 effect reflects the ability of Task 1 related semantic category information from S2 to contribute to Task 1 categorization of S1, on the basis of Task 1 task set rules. The lack of S2-to-R1 influence in Experiment 2 is not surprising, considering that every S2 stimulus was unique; in Experiment 1 and Watter and Logan, repetition of a small set of S2 stimuli may have increased the degree to which Task 1 related semantic information was extracted from S2 during attended performance of Task 1. The continued presence of semantic compatibility effects from S1 on R2 in Experiment 2 with repeated S1 stimuli is consistent with this interpretation.

As a second contrast, our critical Task 2 to Task 1 response compatibility effects were observed convincingly only at the 200-msec SOA in Experiment 2, as compared with both earlier SOAs in Experiment 1. Considering that the same tasks were used in both experiments, with comparable Task 1 RTs across experiments, the unique versus repeated nature of our Task 2 stimuli would appear to be responsible for this difference in time course. To more closely examine this issue, we conducted an additional ANOVA on Task 1 RT data from both Experiments 1 and 2, with experiment as a between subjects variable. There were strong main effects of both response compatibility [$F(1,63) = 14.45$, $MS_e = 3710.18$, $p < .001$] and SOA [$F(2,126) = 15.20$, $MS_e = 27005.75$, $p < .001$]. Semantic and response compatibility factors interacted [$F(1,63) = 3.98$, $MS_e = 4316.27$, $p < .05$], and the interaction of response compatibility with SOA was marginal [$F(2,126) = 2.53$, $MS_e = 3098.26$, $p = .084$]. No significant effects or interactions involving the experiment factor were observed (all *F*s < 1), aside from the non-significant interaction of experiment, semantic compatibility, and SOA [$F(2,126) = 1.87$, $MS_e = 3736.28$, $p = .158$].

These results suggest that the pattern of Task 2 to Task 1 response priming across SOAs and the effect of semantic priming were not significantly different in the two experiments. This analysis also has potential implications for the role of the repeated stimuli used in Experiment 1. Presumably, since every Task 2 stimulus was repeated several times throughout Experiment 1, automatic response activation for Task 2 may have occurred via either direct S-R translation (whether episodic or rule based) or more abstract semantic-category-mediated translation (again, either through learned, episodic

C-R links or concurrently represented task rules). In Experiment 2, using all novel stimuli, automatic generation of Task 2 response information was possible only through category-mediated representations. Since the nature of the response compatibility effect did not appear to differ across experiments, we cannot comment specifically on the influence of specific S-R translation in Experiment 1. It is possible that even with repeating stimuli and the opportunity to learn direct S-R links via episodic or rule-based translation, participants in fact make use of more abstract category-to-response translation.

General Discussion

The goal of the present study was to investigate the nature of R2 information generated in parallel with Task 1 response selection in dual task situations. Experiment 1 ruled out the possibility that R2-to-R1 compatibility effects demonstrated previously by Watter and Logan (2006) were caused by strong S-R representations that developed primarily through experience in Task 1. By employing a unique stimulus set for each task, we were able to demonstrate R2-to-R1 priming when R2 information could be reliably generated only on the basis of the identity of S2 on any given trial, independent of any S1-to-R1 learning or Task 1 mapping rules. Experiment 2 more directly examined the nature of this unattended generation of R2 information from S2, demonstrating R2-to-R1 compatibility effects when a unique S2 stimulus word was presented on every trial. This suggests that R2 information must have been generated from more abstract semantic category information from S2 on every trial, in the absence of any opportunity for direct S-R episodic or specific S-R rule-based influences.

As outlined in the discussion of Experiment 2 above, several potential mechanisms might be considered to account for the unattended generation of R2 information from S2 category information in parallel with Task 1 response selection—namely, an episodic C-R learning process, akin to Hommel's (1998) direct-link framework for automatic S-R translation, versus a more rule-based, nonepisodic but still automatic mapping of activated category representations to appropriate responses. This second account could be conceived of as a more general interpretation of Hommel's transient-link model of automatic S-R translation, where R2 information is generated from the semantic category of S2, rather than mapping directly from S2 to R2. Although our present study cannot readily distinguish between these possible alternatives, both possibilities raise interesting questions regarding the nature of dual-task processing architectures.

An automatic C-R translation account, with episodic category-to-response associations akin to Hommel's (1998) direct-link model, would seem to be more alignable with a traditional RSB account of dual-task performance (Pashler, 1994; Pashler & Johnston, 1998). To make a case to best preserve RSB theory, one might argue that Task 2 response information derived via an episodic process from S2, in parallel with controlled performance of Task 1 response selection, would not meaningfully violate any assumptions of the RSB model. In such a case, the process of mapping stimulus information onto an appropriate response would still be serial and discrete between tasks, with the observed R2-to-R1 compatibility effects considered as an interesting but separate and independent mechanism to response selection.

As discussed by Hommel (1998) and Watter and Logan (2006), the traditional response selection process might be better conceived as a succession of separate response activation and subsequent response selection processes, the latter of which might still be considered as serial and discrete. Hommel suggested that in this situation, response activation potentially begins as soon as stimulus information is available and proceeds in parallel for both tasks in a dual-task situation. Hommel discussed this parallel response activation primarily within the context of specific S-R translations, but the results of our Experiment 2 demonstrate this same parallel response activation with R2 information generated via abstract semantic category-to-response processes. If these rapid automatic C-R translations are the result of multiple task set mappings being held active in working memory and leading to the activation of multiple responses in parallel, our results may be considerably more disruptive to the traditional RSB theory.

This latter possibility would seem to reduce both the extent and scope of what it is that a classical notion of response selection is required to do. As discussed by both Hommel (1998) and Watter and Logan (2006), if response information is typically generated for both tasks in parallel, response selection may be more a process of response gating than an obligatory and heavily computational process. These authors and others (e.g., Logan and Gordon, 2001; Meyer and Kieras, 1997a, 1997b) have also discussed a number of methods by which variably selective serial performance typified by overt bottleneck-like dual-task performance might be a functional solution to inherently parallel dual-task response computation, by allowing a mechanism for resolving cross-task interference, preventing collision of incompatible peripheral actions, and by providing a mechanism for S-R binding with multiple concurrent tasks.

The present study suggests that beyond the repeated-stimulus parallel response priming of Watter and Logan (2006), and beyond the specific S-R accounts of parallel response activation of Hommel (1998), Miller (2006), and Miller and Alderton (2006), parallel generation of response information in dual tasks is substantially mediated via abstract semantic-category-to-response relationships. These findings extend other evidence for automatic semantic-to-response mediation of S-R priming effects (Reynvoet et al., 2002) in dual-task situations, operating in parallel in the unattended task. These findings provide interesting converging evidence for the arrangement of human central information-processing architecture and suggest, along with the results from the other authors cited here, that the classical conception of response selection needs to be reconsidered.

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CHAPTER 3

PRP Training Shows Task1 Response Selection is the Locus of the Backward Response Compatibility Effect

Thomson, S. J., Danis, L. K., & Watter, S.

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Abstract

The present study investigates the effect of practice in a psychological refractory period (PRP) paradigm on the backward compatibility effect (BCE), in order to determine the locus of this response priming effect on Task1 performance. In two experiments, we show that the size of the BCE depends on the duration of the response selection stage in Task1. When this stage is shortened through PRP practice, the magnitude of the BCE decreases. Subsequently increasing the duration of Task1 response selection results in a larger BCE, but manipulating the same stage in Task2 does not. Our results suggest that the BCE reflects crosstalk of unattended response information for Task2 acting on the response selection stage in Task1, and suggest that response information for two tasks may be activated simultaneously.

Introduction

Dual-task interference is often attributed to a bottleneck at the response selection stage of the processing stream (Pashler, 1994), where the response selection stage of the second task cannot begin until this central stage is complete for the first task. In contrast to this idea, a number of crosstalk studies have demonstrated that Task1 performance is influenced by the compatibility relationship between the Task1 and Task2 responses in a psychological refractory period (PRP) paradigm. Specifically, Task1 reaction time (RT1) is shorter when Task2 requires a compatible, rather than incompatible response (Ellenbogen & Meiran, 2008; Hommel, 1998; Miller, 2006; Thomson, Watter, & Finkelshtein, 2010; Watter & Logan, 2006). Compatibility has been defined in a variety of ways across tasks in these studies: identical manual responses, spatially compatible verbal and manual responses (press left key and say “left”), or even corresponding go/nogo responses. Such backward compatibility effects (BCEs) suggest that response information for Task2 is available before Task1 response processing is complete.

There is an emerging consensus that the BCE reflects the priming of the response selection stage in Task1 from the automatically-activated Task2 response; while many findings are consistent with this idea, there is relatively little direct evidence for this assumed Task1 response selection locus. A potential alternative explanation for the BCE is that the response selection stage in Task2 interacts with Task1 during its motor execution stage, after Task1 response selection is complete (e.g., Miller & Alderton, 2006). This alternative interpretation does not conflict with the traditional response selection bottleneck (RSB) model, as it requires no overlap in the response selection processes of the two tasks. Therefore, the precise processing stage that is influenced by response information generated for Task2 is critical for assessing the discreteness assumption of the RSB model. Our goal was to directly test the idea that the BCE is a marker of Task2 response information priming Task1 response selection.

If the BCE reflects priming on Task1 response selection, there are two things that should be important for the presence and magnitude of the BCE: the strength or degree of automatic response activation in Task2, and the degree of susceptibility of response selection in Task1 to the influence of Task2 response information. There is some debate as to whether the automatic activation of Task2 response information producing the BCE is episodically-mediated or driven by multiple task rules held concurrently in working memory (Ellenbogen & Meiran, 2008; Hommel, 1998; Hommel & Eglau, 2002), but it seems clear that the BCE emerges quickly with practice (with typical tasks, often within a single experimental block, on the order of tens of trials). Therefore in this study we chose to manipulate the sensitivity of Task1 response selection to response information generated concurrently for Task2, and measure the effect of this manipulation on the size of the BCE.

One way to manipulate the degree of exposure of Task1 response selection to Task2 response information is to manipulate the duration of Task1 response selection. We predict that the duration of Task1 response selection should be directly related to the size of the BCE. Our approach was to alter the duration of this stage through training. Extensive practice with the PRP paradigm has been shown to reduce dual-task interference (i.e., the PRP effect, assessed as the difference in Task2 reaction time [RT2] at short versus long stimulus onset asynchrony [SOA]; Ruthruff, Johnston, & Van Selst, 2001; Ruthruff, Van Selst, Johnston, & Remington, 2006; Van Selst, Ruthruff, & Johnston, 1999). Strobach, Liepelt, Pashler, Frensch, and Schubert (2013) recently demonstrated that PRP practice primarily reduces the duration of the central response selection stage of processing for each task (see also Pashler & Baylis, 1991), and a number of studies have proposed that it is this central stage shortening that causes the reduction in the PRP effect (Ruthruff et al., 2001; Ruthruff et al. 2006; Strobach et al., 2013; Van Selst et al., 1999).

Our participants practiced an identical PRP task across multiple one-hour training sessions. If the BCE truly reflects priming at the level of Task1 response selection, the magnitude of this effect should also decrease with practice, as Task1 response selection becomes faster and more efficient. This prediction is outlined in Figure 1. Alternatively, if the BCE is the result of priming of the postbottleneck motor stage in Task1, there should be very little influence of practice on the BCE, as the motor stage does not change substantially with practice. In addition, we might predict the Task1 postbottleneck stage to be primed from attended Task2 response selection (rather than automatic Task2 response activation prior to attended Task2 response selection) – in this case, as Task2 response selection becomes faster and more efficient over practice, response information will be produced more quickly relative to the timecourse of Task1 postbottleneck motor execution, which would predict an increase in BCE over practice as relatively more response information is produced from Task2 in the same amount of time.

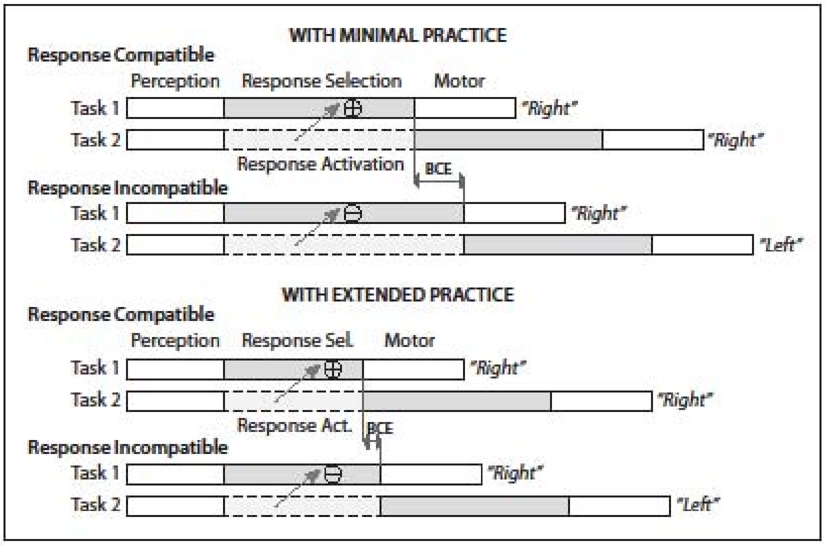

Figure 1. A potential effect of practice on the backward compatibility effect (BCE). The BCE is the difference in reaction time between response compatible and incompatible trials. If the BCE is the result of crosstalk between Task2 response activation and Task1 response selection, the BCE should become smaller with practice as the duration of Task1 response selection is reduced. The top panel demonstrates the BCE with minimal PRP practice, while the bottom panel shows a smaller BCE with extended practice.

We also manipulated the duration of response selection directly in a final session by increasing the number of stimuli in either Task1 (Experiment 1) or Task2 (Experiment 2). This manipulation serves to increase the duration of response selection processing for that task (Karlin & Kestenbaum, 1968; Smith, 1969). Critically, we mapped the additional stimuli onto the existing manual response alternatives, so that response execution demands remained constant. If the BCE depends on the duration of Task1 response selection, lengthening this stage should result in a larger BCE, while increasing the duration of Task2 response selection should not.

Experiment 1

Participants discriminated between letter and color stimuli across seven sessions of a standard PRP task. Each participant completed six identical training sessions, followed by a final test session where two additional Task1 stimuli were included. We expect that the BCE depends critically on the duration of Task1 response selection, which should decrease with practice. Therefore we expect to find that Task1 reaction time (RT1), the BCE, and the PRP effect all decrease across practice sessions and subsequently increase in the final test session when the duration of Task1 response selection is selectively increased with the addition of new stimuli.

Method

Participants. Eleven McMaster University students (eight females) participated in exchange for course credit or monetary compensation[1]. Each participant completed seven sessions within a ten day span, not exceeding one session per day. All participants had normal or corrected-to-normal vision, and all were right-handed.

Apparatus and Stimuli. The stimuli were displayed on a ViewSonic Professional Series P95f+ monitor, controlled by a Dell Dimension 4600 computer. Each trial included two stimuli presented one above the other, centered on a black screen. The first stimulus (S1) was a single capitalized letter, either ‘X’ or ‘Z’, displayed in white Helvetica font, subtending 1° in height and 0.8° in width. The second stimulus (S2) was a colored square, filled in yellow, orange, purple, or blue, subtending 0.9° in height and width. The vertical separation between stimuli was approximately 0.4°. The two stimuli were separated temporally by an SOA of 0, 100, 300, or 900 ms. Participants responded

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[1] Credit and compensation rates implemented incentives and penalties as motivation; rates were determined using each individual’s Task1 accuracy and RT from the previous session.

to each stimulus by pressing the ‘A’ or ‘;’ key on a standard keyboard with the index finger of their left or right hand, respectively.

Procedure. Participants completed six identical training sessions followed by a test session. The tasks were consistent across all sessions. For Task1, participants indicated if S1 was an ‘X’ or ‘Z’; Task2 required them to judge if S2 was ‘warm’ (yellow or orange) or ‘cool’ (purple or blue). Participants were instructed to respond quickly and accurately to each stimulus, but to prioritize Task1 and perform tasks in strict serial order. At the beginning of each trial, a fixation point appeared for 500 ms. This cue was made up of two rows of two white dashes, centered on the screen and separated laterally by approximately 1.1°. Following fixation, S1 appeared alone for the duration of the SOA, and then S1 and S2 were presented together for 1,000 ms followed by a blank screen for 2,000 ms. Task1 and Task2 required the use of the same response keys, thus responses could be either compatible (identical) or incompatible across tasks. Response mapping was counterbalanced across participants but remained consistent for each participant across sessions.

Each session consisted of 512 trials, comprised of 16 blocks of 32 trials with counterbalanced combinations of stimuli and SOAs presented in a randomized order. Sessions began with a practice block of 16 trials that were not included in analysis. At the end of each block participants received feedback regarding their mean RT1 and Task1 accuracy.

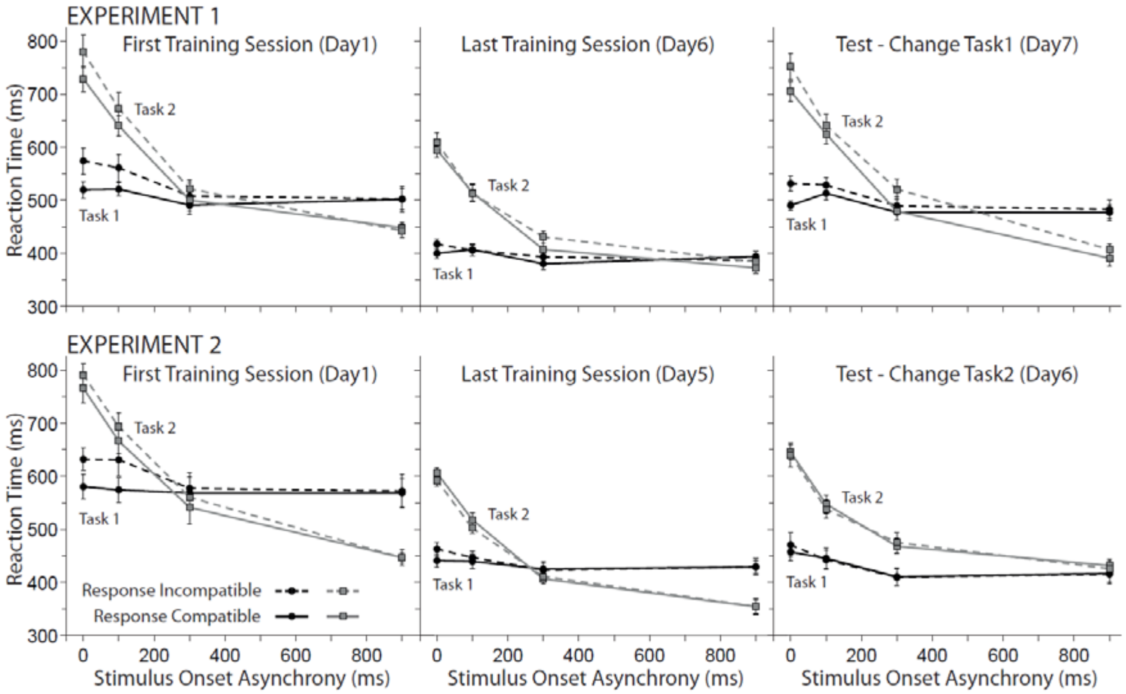

Figure 2. Reaction time data for the first training session, final training session, and test session in Experiments 1 (top) and 2 (bottom). Data for Task1 and Task2 are separated into response compatible and incompatible conditions, and by stimulus onset asynchrony. Error bars represent within-subjects standard errors, adjusted for between-subjects variance based on the entire dataset.

In the test session the letters ‘R’ and ‘U’ were added to the stimulus set for Task1, and all four Task1 stimuli were displayed equally often. ‘R’ was always mapped to the same response key as ‘X’, and ‘U’ was mapped to the same response key as ‘Z’. All other aspects of methodology remained consistent with the training phase. Each participant completed a total of 3,584 trials over seven sessions.

Results and Discussion

One participant was excluded from all analyses for failure to perform the tasks in serial order in the first session. RT trimming for the remaining 10 participants removed .02% of all trials. The top half of Figure 2 shows the mean RTs for Task1 and Task2 as a function of SOA at three time points: the first training session, the last training session, and the test session. Each panel depicts typical PRP performance: RT2 declines substantially with SOA while RT1 remains relatively consistent across SOA. There was a considerable decrease in both RT1 and RT2 from the initial to the final training session.

To investigate the change in BCE across training sessions, we focus on 0 ms SOA trials, where there is the largest temporal overlap between tasks. Mean RT1s were submitted to a 6 (session) x 2 (response compatibility) repeated measures ANOVA. These means are displayed as grey and white bars in the left panel of Figure 3. Response compatible trials were faster than incompatible trials, $F(1,9) = 20.49$, $p = .001$, $\eta_p^2 = .71$, demonstrating a BCE in Task1 performance. RT1 decreased with training, $F(5,45) = 21.70$, $p < .001$, $\eta_p^2 = .70$. Critically, the size of the BCE also decreased reliably across training sessions, as shown by an interaction between response compatibility and session, $F(5,45) = 6.02$, $p < .001$, $\eta_p^2 = .40$. The BCE observed on 0 ms SOA trials varied closely with RT1 at the 0 ms SOA, $r(4) = .939$, $p = .005$. The PRP effect, calculated as the difference in RT2 between 0 ms and 900 ms SOA trials, is plotted for each session in Figure 3 in black. As expected, it also decreased progressively with practice. A one-way ANOVA revealed a significant linear trend, $F(1,9) = 9.88$, $p = .012$, $\eta_p^2 = .52$, in the PRP effect across training sessions.

In the test session following the training phase, the Task1 stimulus set was doubled from two letters to four, in order to increase the duration of Task1 response selection. We are confident that this task manipulation primarily influenced the central response selection stage, and not the postbottleneck motor stage of Task1, since the increase in RT1 relative to the final training session was largely propagated onto RT2, except at the longest SOA where Task1 response selection was most frequently completed before the Task2 stimulus appeared (mean increases of 102, 115, 96, and 90 ms in Task1 at the 0, 100, 300, and 900 ms SOAs, respectively, translated to increases of 127, 119, 84, and 21 ms at these SOAs in Task2).

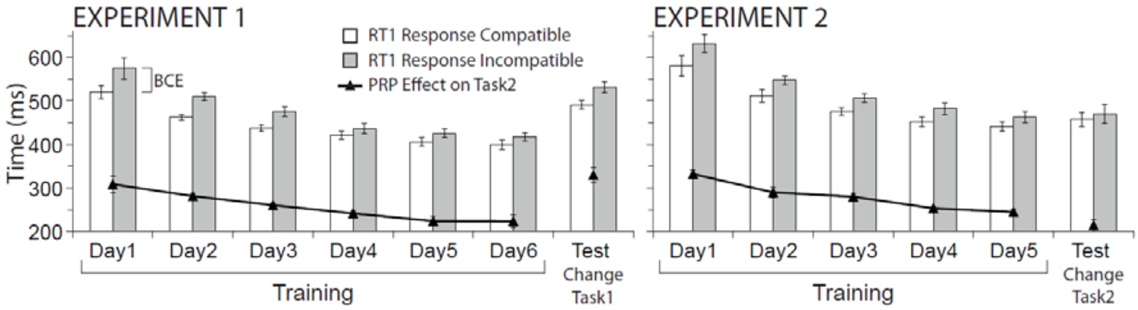

Figure 3. White and grey bars depict reaction time data for Task1 on 0 ms stimulus onset asynchrony (SOA) trials in Experiments 1 (left) and 2 (right), for response compatible and incompatible trials respectively; the difference between each pair of bars is the backward compatibility effect (BCE). The PRP effect (difference in Task2 reaction time between 0 and 900 ms SOA trials) is plotted over sessions in black. The BCE and PRP effect become smaller across training sessions in both experiments. BCE and PRP effects increase significantly between training and test in Experiment 1 but not in Experiment 2. Error bars represent within-subjects standard errors, adjusted for between-subjects variance based on 0 ms SOA data across all sessions, and reflect variances contributing to reported statistical analyses.

We compared RT1 on 0 ms SOA trials in the test session to the final practice session using a 2 (session) x 2 (response compatibility) ANOVA, which revealed significant main effects of session, $F(1,9) = 42.36$, $p < .001$, $\eta_p^2 = .86$, response compatibility, $F(1,9) = 16.57$, $p = .003$, $\eta_p^2 = .65$, and most importantly an interaction between these factors, $F(1,9) = 14.27$, $p = .004$, $\eta_p^2 = .61$, indicating that the BCE was larger in the test session where the duration of Task1 response selection was increased.

The PRP effect on RT2 increased significantly from the final training session to the test session as well, *t*(9) = 4.83, *p* = .001, *d* = 1.53. We also looked for any difference in RT1 or response compatibility between the old and new stimuli on 0 ms SOA trials in the final session. A 2 (stimulus type: old/new) x 2 (response compatibility) ANOVA produced a main effect of response compatibility, *F*(1,9) = 19.31, *p* = .002, η_p^2 = .68. There was no effect of stimulus type, *F*(1,9) = 2.29, *p* = .164, η_p^2 = .20, indicating that the test manipulation affected RT1 for both old and new stimuli. The interaction was not significant, (*F*<1, η_p^2 = .03), indicating the size of the BCE was also consistent across old and new stimuli.

Finally, we examined the mean combined Task1 and Task2 error rates on 0 ms SOA trials using repeated measures ANOVAs identical to those for the RT1 data. Error data are summarized in Table 1. Although errors were determined on a trial-wide basis including both tasks, more than 70% of all errors occurred in Task2 performance. Error rates did not vary across training sessions, *F*(5,45) = 1.25, *p* = .30, η_p^2 = .12, but response compatible trials were consistently more accurate than incompatible trials, *F*(1,9) = 9.93, *p* = .012, η_p^2 = .53, with no interaction, *F*<1. As compared with the final training session, performance in the test session was much less accurate, *F*(1,9) = 25.59, *p* < .001, η_p^2 = .77. A main effect of response compatibility, *F*(1,9) = 14.46, *p* = .004, η_p^2 = .62, was modified by an interaction with session, *F*(1,9) = 5.85, *p* = .039, η_p^2 = .39, indicating that the compatibility effect was larger in the test session.

To summarize, Experiment 1 replicates previous work showing a reduction in the PRP effect with practice; importantly, we show BCE magnitude also decreases with

Table 1. Mean dual-task error rates (% Error) and standard errors of the mean (SEM) for 0 ms SOA trials in Experiment 1 and Experiment 2.

	Experiment 1				Experiment 2			
	Compatible		Incompatible		Compatible		Incompatible	
Session	% Error	(SEM)	% Error	SEM	% Error	SEM	% Error	SEM
1	0.07	(0.02)	0.16	(0.04)	0.06	(0.02)	0.07	(0.02)
2	0.07	(0.01)	0.12	(0.03)	0.04	(0.01)	0.09	(0.03)
3	0.07	(0.02)	0.15	(0.05)	0.06	(0.01)	0.07	(0.02)
4	0.08	(0.02)	0.15	(0.03)	0.05	(0.01)	0.09	(0.02)
5	0.09	(0.02)	0.15	(0.04)	0.04	(0.01)	0.09	(0.03)
6	0.09	(0.02)	0.16	(0.04)	0.08	(0.03)	0.11	(0.03)
7	0.13	(0.03)	0.28	(0.05)				

Note. Error rates reflect errors on either Task 1 or Task 2 of a particular trial, and are divided by the response compatibility relationship between tasks.

practice, closely tracking the decline in RT1. Since RT1 reduction with practice primarily reflects response selection shortening (Pashler & Baylis, 1991; Strobach et al., 2013), we suggest that the BCE reflects unattended Task2 response information priming the response selection stage in Task1. Further evidence supporting this hypothesis comes from the test session, where increasing the duration of Task1 response selection following training led to a larger BCE. These findings are not predicted by a postbottleneck locus for the BCE in Task1 performance.

Experiment 2

Experiment 2 provides a second test of the hypothesis that the BCE depends specifically on the duration of Task1 response selection. We conducted a conceptual replication of the training phase in Experiment 1 with alternative materials, followed by a test session with additional stimuli added to Task2 (instead of Task1 as in Experiment 1). This manipulation should not affect response selection in Task1, and therefore if the BCE depends on the duration of this stage it should not increase in the final session, in comparison to Experiment 1.

Method

Participants. Ten individuals from McMaster University (six females) participated in the experiment, nine were right-handed, and none had completed Experiment 1.

Apparatus, Stimuli and Procedure. Aside from the following changes, the method was identical to Experiment 1. S1 was an 'H' or an 'S'; S2 was a white-filled shape, either a square or a triangle, with a height and width of approximately 1.25° of visual angle. The participants were to identify the letter for Task1 and the shape for Task2. Participants completed five identical training sessions, followed by a test session in which a pentagon and a circle were added to the stimulus set for Task2. The pentagon was mapped to the same response as the triangle and the circle was mapped to the same response as the square. Each participant completed 3,072 trials over six sessions.

Results and Discussion

RT trimming removed .14% of all trials. Mean RTs for Task1 and Task2 as a function of SOA are shown in the lower half of Figure 2 for the first and final training sessions and the test session. Each panel depicts typical PRP performance. The right half of Figure 3 shows mean RT1 at the 0 ms SOA for response compatible and incompatible trials, as well as the PRP effect across sessions. A 5 (session) x 2 (response compatibility) repeated measures ANOVA on 0 ms SOA data revealed that RT1 decreased with training, $F(4,36) = 19.71$, $p < .001$, $\eta_p^2 = .69$. A main effect of response compatibility, *F*(1,9) = 38.46, $p < .001$, $\eta_p^2 = .81$ was modified by an interaction with session, *F*(4,36) = 2.70, $p = .046$, $\eta_p^2 = .23$, showing that the BCE decreased across training sessions. Once again the BCE and RT1 at the 0 ms SOA were highly correlated across training sessions, *r*(3) = .97, $p = .005$. The PRP effect also decreased progressively with practice, with a significant linear contrast, *F*(1,9) = 31.03, $p < .001$, $\eta_p^2 = .78$.

In the test session, the Task2 stimulus set was doubled from two shapes to four in order to increase the duration of Task2 response selection. This manipulation increased RT2, but not RT1, relative to the final practice session (average increase in RT1 of -4 ms, average increase in RT2 of 53 ms; see Figure 2). Repeated measures ANOVA conducted on RT1 at the 0 ms SOA for the final training and test session confirmed that RT1 did not change significantly ($F<1$ $\eta_p^2 = .09$). A main effect of response compatibility, *F*(1,9) = 8.79, $p = .016$, $\eta_p^2 = .49$, with no interaction with session, *F*(1,9) = 2.01, $p = .19$, $\eta_p^2 = .18$, indicated that, unlike in Experiment 1, the size of the BCE did not change between the final training and test sessions. Additionally, the PRP effect was significantly smaller in the test session than in the final training session, *t*(9) = 3.34, $p = .009$, $d = 1.06$. RT1 in the test session was marginally faster on 0 ms SOA trials when the stimulus in Task2 was old rather than new, *F*(1,9) = 3.83, $p = .082$, $\eta_p^2 = .30$, although the size of the BCE did not differ as a function of stimulus type ($F<1$, $\eta_p^2 = .01$).

Finally, we examined the mean combined Task1 and Task2 error rates on 0 ms SOA trials as in Experiment 1. More than 80% of errors occurred in Task2 performance. Error rates did not change across training session ($F<1$). Response compatible trials were marginally more accurate than incompatible trials, *F*(1,9) = 4.04, $p = .075$, $\eta_p^2 = .31$, and observed variability in this effect across sessions produced an interaction between response compatibility and session, $F(4,36) = 2.63$, $p = .050$, $\eta_p^2 = .23$. As in Experiment 1, performance in the test session was less accurate as compared with the final training session, $F(1,9) = 12.05$, $p = .007$, $\eta_p^2 = .57$. Once again we observed a main effect of response compatibility, $F(1,9) = 12.91$, $p = .006$, $\eta_p^2 = .59$, but, unlike in Experiment 1, this effect did not differ between the final training and test sessions ($F<1$).

To summarize, in Experiment 2 we replicated the training effects observed in Experiment 1: RT1, the BCE, and the PRP effect all decreased with practice, and RT1 and the BCE were closely correlated across sessions. Adding stimuli to Task2 in the test session to lengthen Task2 response selection had no effect on the BCE – this is in sharp contrast to the effect of lengthening Task1 response selection in Experiment 1, which resulted in a large increase in the magnitude of the BCE. These data provide converging evidence that the BCE depends specifically on the duration of Task1 response selection, and that the effect represents crosstalk from Task2 response activation occurring in parallel with response selection in Task1.

General Discussion

Reduction in RT with PRP practice primarily reflects shortening of the response selection stage of processing (Pashler & Baylis, 1991; Strobach et al., 2013). Our experiments show that practice also produces a decrease in the BCE closely correlated with reduction in RT1. Our final test sessions demonstrate that the BCE depends selectively on Task1 response selection; manipulating Task2 response selection does not influence the BCE. These findings indicate a Task1 response selection locus for the BCE, and argue against a postbottleneck effect. These findings suggest the traditional RSB theory requires modification to account for generation of Task2 response information in parallel with Task1 response selection.

The results of the test session in Experiment 2 show that the BCE does not depend on the duration of attended Task2 response selection. This may seem surprising, since we have shown that the BCE itself is a measure of response information generated for Task2 interacting with Task1 performance. Our interpretation of these findings in Experiment 2 is that the Task2 response information driving the BCE is generated automatically, and that this automatic response information is separate from response selection for Task2 that proceeds after attention switches from Task1 to Task2. Hommel (1998) proposed distinct serial stages of response activation and response selection in describing BCEs, although Thomson & Watter (2013) demonstrated that this early response information for Task2 can sometimes influence later Task2 response selection, which suggests that these activation and selection stages may not be fully discrete.

The present study provides converging evidence for a Task1 response selection locus of the BCE, and argues against a postbottleneck motor response execution locus of this effect. These findings lend support to interpretations of the BCE as reflecting parallel generation of response information for both tasks in a PRP paradigm. We suggest that more nuanced models of response selection processes are required to better account for these kinds of data.

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CHAPTER 4

Information Continuity across the Response Selection Bottleneck: Early Parallel Task 2 Response Activation Contributes to Overt Task 2 Performance

Thomson, S. J. & Watter, S. (2013).

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Abstract

Several studies of dual-task performance have demonstrated Task 2 to Task 1 response priming (backward compatibility effects), indicating some degree of parallel response computation for concurrent tasks, and suggesting that the well-established response selection bottleneck (RSB) model may be incomplete. However, the RSB might be considered to remain informationally intact if this early parallel Task 2 response information does not persist across the attentional shift between tasks to contribute to overt Task 2 performance. We used an adapted psychological refractory period paradigm with an additional early transient Task 2 stimulus to examine whether response information generated for Task 2 in parallel with overt Task 1 response selection could persist across the bottleneck to influence eventual overt Task 2 performance. After controlling for potential indirect effects of Task 1 processing stage variability propagating onto Task 2 reaction time via locus of slack effects, we observed reliable and consistent effects of early Task 2 response information facilitating Task 2 reaction times. These effects were observed only when the responses to both tasks of the dual-task pair were compatible, under both univalent and bivalent response mappings across tasks. These findings may represent evidence of a variably sensitive response gating or suppression mechanism in dual-task performance, and support the idea that backward response compatibility effects represent transient informational influences on central response codes, rather than later post-bottleneck response execution processes.

Introduction

People commonly experience difficulty in performing multiple tasks concurrently. This limitation in human performance has been studied extensively using the psychological refractory period (PRP) paradigm. In these studies, participants are presented with two stimuli and are asked to perform a given task for each in succession. The stimulus onset asynchrony (SOA) is varied, and the typical finding is that while the first task is unaffected by SOA, the time required to perform the second task increases as the SOA decreases and the two tasks overlap more in time. This PRP effect is taken as empirical evidence of a fundamental limitation in human central information processing.

The delay in performance for the second of two tasks can be explained by the RSB theory (Pashler, 1984, 1994; Pashler & Johnston, 1998) and the related locus of slack logic. According to RSB theory, processing can proceed in parallel for two tasks until they reach a central stage of processing that can be performed only for one task at a time. If processing of the second task reaches the bottleneck stage while this stage is still occupied by Task 1, Task 2 processing is temporarily suspended until Task 1 completes the bottleneck process and Task 2 can gain access to it. The bottleneck is presumed to be in the stage of response selection, where the response to a task is selected according to task set mapping rules. Pre- and postbottleneck processing stages of the two tasks can proceed in parallel; only the bottleneck stage in each task cannot overlap. This basic model is demonstrated in Fig. 1a.

Evidence for Parallel Response Selection

While the RSB theory has proven to be quite robust and has been able to explain a wide range of results in dual-task studies, it has been challenged by several studies demonstrating an influence of Task 2 response selection processing on Task 1 performance. For instance, Hommel (1998) found that participants were faster to make a manual left/right response in Task 1 if Task 2 required a related vocal response (saying "left" or "right"). The presence of these backward compatibility effects implies that the response to Task 2 was activated before response selection for Task 1 was complete. Several other studies of backward cross talk in more traditional PRP paradigms have provided converging evidence that response information for Task 2 is activated early enough to influence Task 1 responding (Miller, 2006; Miller & Alderton, 2006; Thomson, Watter, & Finkelshtein, 2010; Watter & Logan, 2006). As is demonstrated in Fig. 1b, manual responses to Task 1 have been shown to be faster if the response key required for Task 2 is identical to that required for Task 1, relative to when the two responses are different (e.g., Thomson, et al., 2010; Watter & Logan, 2006). Moreover, this Task 2 to Task 1 response priming can occur even for Task 2 stimuli that have not previously been encountered, suggesting that Task 2 response information can be automatically activated from semantic category representations of the Task 2 stimulus, independently of specific stimulus-response relationships (Thomson, Watter, & Finkelshtein, 2010). Such findings imply that at least some portion of Task 2 response selection is occurring in parallel with Task 1, which would seem to be incompatible with a strict RSB account of dual-task performance.

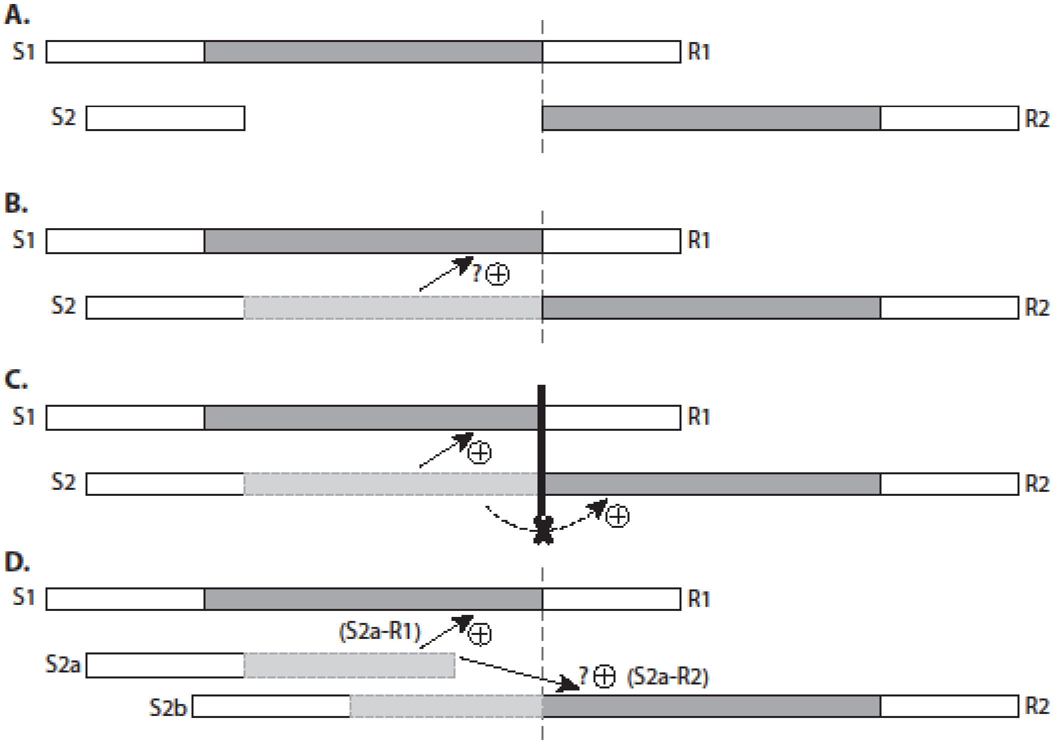

Fig. 1 Possible variations in dual task processing at short SOAs. Dark gray shading indicates the response selection stage; light grey shading indicates response activation in Task 2 operating in parallel with Task 1 response selection. **a** The traditional Response Selection Bottleneck model. **b** The Task 2 to Task 1 response priming effect demonstrated by Hommel (1998), Watter and Logan (2006), and others ("+" indicates response compatibility). **c** Illustration of the potential for suppression of response activation following the completion of Task 1 response selection to preserve a strict informational bottleneck in response selection. In this situation, early parallel Task 2 response information can prime Task 1 response selection but does not influence overt Task 2 response selection. **d** The design of the present experiments, to test whether early parallel Task 2 response information can influence the eventual Task 2 response. Presenting a brief transient Task 2 stimulus (S2a) prior to the main Task 2 stimulus (S2b) allows the observation of potential response compatibility effects of early parallel S2a-related response information on the overt Task 1 response (S2a-R1 compatibility) and the overt Task 2 response (S2a-R2 compatibility).

There are a number of accounts of parallel response selection mechanisms in dual tasks. According to Meyer and Kieras's (1997a, b) executive process interactive control (EPIC) architecture, response selection may proceed in parallel for two tasks but participants strategically defer their responses for the second task. In Logan and Gordon's (2001) executive control theory of visual attention (ECTVA), the two tasks may be processed in parallel but PRP performance is improved when the tasks are performed serially because of reduced interference between tasks. In accounting for his Task 2 to Task 1 response priming data, and mindful of the substantial and persistent Task 2 reaction time (RT) costs even in the presence of parallel response activation, Hommel (1998) suggested a model of separate stimulus-response translation (or response activation) and subsequent response selection processes to replace the traditional unified stage of response selection. The first of these distinct processes can occur automatically and in parallel with processing in a separate task and results in the activation of a response. Afterward, controlled rule-governed processes guide the ultimate selection of the response for each task in a serial fashion. The serial nature of this later response selection stage results in delayed execution of the second task. This version of a bottleneck model does not include the computation of responses in its bottleneck stage. In considering Hommel's (1998) model, however, Watter and Logan (2006) questioned the nature of the later serial selection stage. Specifically, if the work of accruing response information from stimuli and activating a response for each task is completed in the initial parallel response activation stage, what work is then left for the serial response selection stage that supposedly is the source of the processing delay? In this situation, the serial response selection process takes on a very different character than typically described and tested in traditional locus of slack PRP studies.

The Fate of Response Information for Task 2 Generated in Parallel with Task 1

Accumulating dual-task findings have argued for Task 2 response information being generated in parallel with Task 1 performance and prior to completion of Task 1 response selection. However, an alternative account is suggested by the persistence of large RT costs on Task 2 performance. It is possible that the parallel response activation for Task 2, reflected by Task 2 to Task 1 response priming effects observed by Hommel (1998), Watter and Logan (2006), Miller (2006), and others, may not actually involve any influence on eventual attended Task 2 performance. Instead, early response activation for Task 2 may occur entirely automatically and in parallel with attended Task 1 performance, but when participants' attention subsequently switches to Task 2, any response information that has been generated up to that point is disregarded and does not contribute to the actual performance of the second task. This possibility is illustrated in Fig. 1c. This account preserves the spirit of the RSB theory, since response selection for Task 2 must essentially start over once attention is focused on this task, and it can also explain the influence of Task 2 processing on Task 1 performance. Importantly, the phase of response selection that actually contributes to attended performance of Task 2 is functionally and informationally discrete from the response selection stage of Task 1.

The idea that any Task 2 response information derived in parallel with Task 1 response selection may not be used in the eventual selection of a response for Task 2 is not new. Computational models of dual-task performance such as ECTVA (Logan & Gordon, 2001) employ response inhibition mechanisms between tasks in order to prevent response perseveration and interference from Task 1 processing. Inhibiting or resetting response counters after Task 1 response selection is complete would also result in the loss of any partial activation of response information for Task 2 generated in parallel with Task 1, so that this information has no influence on attended Task 2 performance. According to this view, the Task 2 to Task 1 priming studies mentioned previously do not directly address the discreteness assumption of the RSB theory. From this view, the critical test of the informational bottleneck idea is not backward response priming from Task 2 to Task 1 but, instead, priming from early unattended Task 2 response information to subsequent attended Task 2 performance. Does Task 2 response information generated automatically and in parallel with Task 1 response selection persist beyond the bottleneck and the attentional shift from Task 1 to Task 2, in order to influence actual Task 2 performance?

Schubert, Fischer, and Stelzel (2008) recently addressed this question. They used a PRP paradigm where participants discriminated between tones for Task 1 and judged the direction of a visually presented arrow for Task 2. Importantly, the Task 2 stimulus was preceded by a subliminal prime arrow that was congruent, incongruent, or neutral with respect to the target arrow. Schubert et al. measured the effect of Task 2 prime congruency on Task 1 and Task 2 RTs (RT1 and RT2) and observed an underadditive prime congruency effect in RT2 that was significant at short stimulus onset asynchronies (SOAs).

The authors considered two alternative models of how response activation arising from the early Task 2 prime stimulus could affect Task 2 performance. One possibility is that response information generated for the Task 2 prime stimulus in parallel with attended Task 1 processing persists across the bottleneck to directly influence Task 2 response selection. They labeled this option the *bypass model*. Alternatively, according to the *indirect influence model*, response activation for the Task 2 prime stimulus has no direct access to attended response selection in Task 2. Instead, a mechanism mediated solely by cross talk between tasks mimics the effects of the bypass model. On response-compatible trials, cross talk from Task 2 to Task 1 leads to a shortening of Task 1 prebottleneck or bottleneck processing stages. The bottleneck stage of Task 2 can therefore begin earlier and shorten the overall duration of Task 2 by the same amount. Conversely, on incompatible trials, cross talk from Task 2 to Task 1 lengthens these Task 1 stages, and as a result, Task 2 processing is further delayed. In these situations, bottleneck or later processing stages of Task 2 are not influenced by response information from early Task 2 prime stimuli directly, but RT2 is shortened or lengthened due to propagated Task 1 effects via the locus of slack at short SOAs. In this view, the accumulated response information for Task 2 is reset or otherwise does not actually contribute to later Task 2 processing.

Schubert et al. (2008) found a congruence effect between the prime and target Task 2 stimuli only in situations where informational overlap existed between tasks, allowing for the possibility of response information cross talk from Task 2 to Task 1 and subsequent indirect propagation of Task 2 congruency effects onto RT2. In addition, the magnitude of the Task 2 congruency effects were observed to be equivalent in both RT1 and RT2, providing further support for the indirect mediation of Task 2 congruency effects. From these results, Schubert et al. concluded that early response activation for

Task 2 does not bypass the RSB and does not persist to directly influence overt Task 2 performance.

The Present Study

The goal of the present study was to provide an additional test of the bypass model. The question of whether information can persist across the RSB is critical to the RSB theory specifically and to our understanding of dual-task processing in general. Evidence of parallel response selection alone is not sufficient to contradict the bottleneck model if the result of this processing does not contribute to secondary task performance. In fact, this resetting of accumulated response information would resolve the apparent paradox of backward compatibility effects in RT1 despite the persistence of substantial dual-task costs observed in RT2. However, demonstrations of information continuity across the bottleneck would be incompatible with central assumptions of the RSB theory. Given these important implications, we feel that it is worthwhile to investigate this issue further.

We employed a design that could independently assess response compatibility priming between tasks, as well as potential influences from early parallel response activation in Task 2 to later overt Task 2 performance. Our design involved a typical PRP paradigm with different tasks for Task 1 and Task 2. We used a stimulus substitution technique, similar to that in Schubert et al. (2008), where the initial stimulus for Task 2 (S2a) was replaced by a second, target Task 2 stimulus (S2b) after a short 200-ms interval, with participants told to ignore the early transient S2a and respond to the subsequent S2b, presented for 1,000 ms. This allowed us to assess the influence of any response information potentially generated for this initial transient S2a stimulus on both Task 1 processing (by examining backward response compatibility from Task 2 to Task 1), and eventual explicit Task 2 performance. Our transient stimulus was displayed substantially longer than that of Schubert et al. (only 34 ms), which may provide a better opportunity for sufficiently strong response activation to persist across the bottleneck (although for a demonstration of subliminal Task 2 primes generating compatibility effects in Task 1 and Task 2, see Fischer, Kiesel, Kunde, & Schubert, 2011).

Our general design is shown in Fig. 1d. If response information is generated for the transient S2a in parallel with response selection processes in Task 1, we expect to find evidence of Task 2 to Task 1 response compatibility effects from the S2a stimulus (S2a-R1 compatibility on RT1) similar to those demonstrated by Watter and Logan (2006), Miller (2006), Miller and Aldterton (2006), and Thomson et al. (2010), even though S2a itself did not require a response. Additionally, we assessed Task 2 for the potential influence of S2a compatibility on explicit Task 2 performance (S2a-R2 compatibility on RT2), and we expect results similar to those of Schubert et al. (2008), where this effect was underadditive with SOA, but still prominent even at short SOAs. We also assessed both Task 1 and Task 2 for expected effects of response compatibility between tasks (R1-R2 compatibility on both RT1 and RT2, not illustrated in Fig. 1d).

Critically, after observing S2a-R2 compatibility effects on Task 2, we conducted subsequent analyses on short SOA data to more conclusively assess whether this Task 2 effect was mediated by the indirect propagation of Task 2 to Task 1 prebottleneck or bottleneck cross talk effects onto RT2 (as suggested by Schubert et al., 2008) or whether, instead, response information generated from S2a could be observed to directly influence RT2 independently of any indirect propagation via Task 1. For this analysis, we calculated the difference between RT1 and RT2 on each correct trial and used this difference score as the dependent measure. For short-SOA data, subtracting the RTs for Task 1 from those of Task 2 should equate RT2 measures for any duration differences in Task 1 pre-bottleneck or bottleneck stages—in our present case, removing potential effects of priming of R1 from S2a response information that might propagate onto RT2. If this indirect propagation of Task 1 priming effects from S2a is solely responsible for the S2a-R2 compatibility effect observed in the previous RT2 analysis, we should observe no S2a-related compatibility effects on these adjusted RT2 scores. If, however, a sufficient amount of response information generated from S2a in parallel with Task 1 processing persists across the bottleneck to influence overt Task 2 performance, we would expect to still find S2a compatibility effects at short SOAs in the adjusted RT2 data. The latter case would suggest that S2a-related response information was able to bypass the bottleneck and directly influence overt Task 2 performance.

It is important to note that this type of analysis is relevant only at short SOAs, when processing in Task 2 is delayed by the bottleneck stage in Task 1. At longer SOAs, Task 2 is less affected by (or eventually, independent of) bottleneck processing delays from Task 1, and therefore, subtracting RT1 from RT2 becomes less meaningful. For this reason, this analysis was conducted only for our shortest two SOAs (0 and 100 ms), where a strong PRP effect was observed, with a slope approaching -1 across compatibility conditions.

Experiment 1

Participants performed a PRP task. For Task 1, they were presented with a letter and were asked to indicate with a manual keypress response whether the letter was an X or a Z. Task 2 was a color discrimination task with two colors mapped to each response. Importantly, there were two Task 2 stimuli presented on every trial. The first, S2a, was presented briefly, and participants were instructed to ignore it. The second, S2b, replaced S2a after 200 ms, and it was to the latter Task 2 stimulus that participants made their response. The analysis investigated whether a response was selected for S2a in parallel with Task 1 performance and whether this response information was able to bypass the bottleneck to contribute to subsequent Task 2 performance.

Method

Participants. Twenty undergraduate students enrolled in psychology courses at McMaster University (15 females) participated in the experiment for partial fulfillment of course credit. All had normal or corrected-to-normal vision, and all were right-handed.

Apparatus and Stimuli. The experiment was conducted on a Dell Dimension 4600 computer using a ViewSonic Professional series P95f+ monitor and Presentation® (v.13, www.neurobs.com) experimental software. The stimuli for Task 1 were the letters X and Z, and for Task 2 they were squares presented in red, green, blue, or yellow. The letters were always presented in white, and all stimuli were presented against a black background. Participants sat at a viewing distance of approximately 60 cm, and from this distance the square stimuli subtended 0.9° of visual angle in height and width, and the letter stimuli subtended 1° degree of visual angle in height and 0.8° in width. Stimuli were presented centrally, with letter stimuli for Task 1 always presented above the colored square stimuli for Task 2, with a vertical separation between the nearest edges of Task 1 and Task 2 stimuli of approximately 0.4°.

Procedure. For the Task 1 stimulus (S1), participants performed a letter discrimination task, indicating whether the letter stimulus was an X or a Z. For Task 2, participants were instructed to ignore the first S2a "distractor" square and respond only to the second S2b "target" square, by pressing one key if the target square was either red or yellow or a different key if the square was either blue or green. Participants made separate responses to each task by pressing the "1" or "2" key on the number pad of a standard keyboard with the index or middle finger of the right hand, for each task in sequence. The response mapping for each task was counterbalanced across participants, and a card was attached to the bottom of the monitor to remind participants of the mapping for their condition. Task 1 and Task 2 were separated in time by an SOA of 0, 100, 300 or 900 ms, defined as the separation of stimulus onset for S1 and S2a, with S2b replacing S2a 200 ms following S2a presentation.

The sequence of a single trial is illustrated in Fig. 2. Every trial lasted 4,000 ms and began with a fixation display for 500 ms. This display consisted of two rows of two dashes centered on the screen, separated laterally in each row by approximately 1.1° of visual angle, flanking the locations where the stimuli for each task would appear. On zero SOA trials, this display was replaced by a display containing a letter (S1) and a colored square (S2a) for 200 ms, after which S2a was replaced with the target coloured square S2b. S1 and S2b were presented together for 1,000 ms, followed by a blank screen for

2,300 ms. On nonzero SOA trials, the fixation display was replaced with a display containing only S1 for the duration of the SOA, after which S2a was added for 200 ms, before being replaced by S2b. S1 and S2b remained onscreen together for 1,000 ms, followed by a blank screen for the remainder of the trial duration. Each stimulus and SOA duration were presented an equal number of times, with the constraint that each S2a distractor was always followed by either the other color requiring the same response (compatible) or a consistent one of the two potential incompatible colors, each with equal probability. For example, a blue S2a was followed by a green S2b (response compatible) 50% of the time, and the other 50% of the time, it was followed by a red S2b (response incompatible). It was never followed by the other incompatible (yellow) S2b. The design was balanced such that neither the specific S2b color nor the response compatibility could be reliably predicted from S2a, and the S2a and S2b colors were never identical on a given trial.

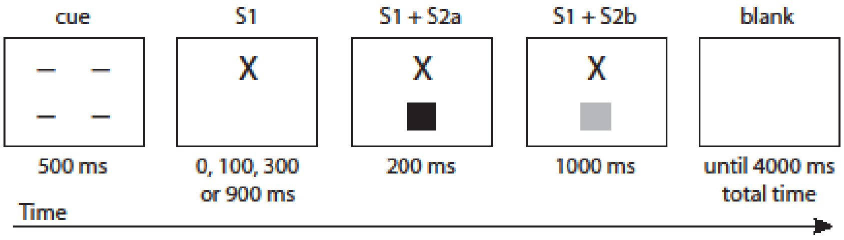

Fig. 2 The sequence of task elements within a single trial for Experiments 1 and 2. In Experiment 1, participants responded to Task 1 and then Task 2 with the index versus middle fingers of the same hand (bivalent mapping). In Experiment 2, participants responded with the index versus middle fingers of one hand for Task 1 and then with the index versus middle fingers of their other hand for Task 2 (univalent mapping). Task 1 required participants to respond to S1 letter identity (‘X’ vs. ‘Z’). Task 2 required participants to respond to S2b colour (red or yellow vs. blue or green) and ignore the initial transient S2a.

Participants were told that the experiment was a test of their concentration, to investigate how effectively they could complete simple tasks presented in quick succession. They were instructed that Task 1 was most important and that they should concentrate fully on this first task until its completion before attending to the colored square for Task 2. It was explicitly stated that they should not wait until the stimuli for both tasks were displayed before making their response to S1 but, instead, should be as quick and accurate as possible for each task in turn. Participants were informed of S2a but were told that this stimulus was irrelevant and were encouraged not to be distracted by it.

The experiment consisted of 512 trials, made up of eight iterations of the factorial combination of the two letter stimuli for Task 1, the four colors for S2a, the two potential colours that followed each as S2b (compatible or incompatible), and the four SOAs. Trials were presented in random order across 12 blocks, with 11 blocks of 43 trials and a final block of 39 trials. Participants were given the opportunity to rest before initiating the beginning of each block. Before the experimental trials began, participants completed a practice block of 32 trials that were not considered for analysis.

Data Analysis. Data were analyzed from participants who completed Task 1 and Task 2 correctly on at least 70% of the trials. Trials with RTs less than 200 ms were excluded from analysis, as well as trials with RT1 greater than 1,500 ms or RT2 greater than 2,000 ms. Mean RTs for each condition were computed from the remaining trials where both Task 1 and Task 2 were correct. The initial analyses assessed the influence of response priming from both Task 2 stimuli (S2a and S2b) on Task 1 performance, as well as response priming in Task 2 from both Task 1 and the distractor S2a. For Task 1, we evaluated the response compatibility between Task 1 and Task 2 responses (R1-R2 compatibility), as well as the compatibility between R1 and the theoretical response to S2a (S2a-R1 compatibility)[2] over each SOA, and submitted the mean Task 1 RTs to a 2 (R1-R2 compatibility) x 2 (S2a-R1 compatibility) x 4 (SOA) repeated measures ANOVA with all factors considered within subjects. For Task 2, we again evaluated R1-R2 compatibility between tasks and also assessed within task response compatibility between the to-be-ignored S2a and R2 (S2a-R2 compatibility). Mean RTs were submitted to a 2 (R1-R2 compatibility) x 2 (S2a-R2 compatibility) x 4 (SOA) repeated measures ANOVA, again treating all factors as within subjects.

Error data were evaluated separately for each task. Trials with an error committed on Task 1, regardless of Task 2 accuracy, were assessed with respect to Task 1 R1-R2 and S2a-R1 compatibility conditions, akin to RT data. Trials with an error committed on Task 2 after accurate Task 1 performance were assessed according to Task 2 R1-R2 and S2a-R2 compatibility conditions, again akin to RT data. Participants' error rate data for each task were submitted to the same separate three-way repeated measures ANOVAs as that used for the RT analyses.

Finally, to directly test whether S2a-R2 effects observed in Task 2 were the result of indirect locus of slack effects from Task 1 or, instead, suggestive of S2a response information bypassing the bottleneck and directly influencing overt Task 2 performance,

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[2] We chose our compatibility labels to distinguish between the compatibility between two executed responses (R1-R2, responses here made to S1 and S2b) and the compatibility between a stimulus that did not require a response and an executed response (i.e., S2a-R1 and S2a-R2). S2a-R2 compatibility here is analogous to the "congruence" manipulation in Schubert et al. (2008).

we conducted an analysis with data from short SOAs, using the difference between RT1 and RT2 as the dependent measure. For every trial with correct Task 1 and Task 2 performance, the RT for Task 1 was subtracted from that for Task 2, and mean adjusted RT2 data were submitted to a 2 (R1-R2 compatibility) x 2 (S2a-R2 compatibility) x 2 (SOA) repeated measures ANOVA.

Results

One participant was excluded from the analysis for failure to meet the accuracy criterion of 70% correct trials. RT trimming removed an average of 2.4% of trials from each of the remaining 19 participants' data. Mean RTs for the remaining trials with correct Task 1 and Task 2 performance are displayed in Fig. 3.

Task 1 Reaction Time. The analysis revealed no main effect of S2a-R1: Mean RTs did not differ across S2a-R1 compatibility conditions, $F(1, 18) < 1$. Additionally, the main effect of R1-R2 compatibility did not reach significance, $F(1, 18) = 2.12$, $p = .16$. However, we found an interaction between these two factors, $F(1, 18) = 28.40$, $MSE = 772.28$, $p < .001$, demonstrating that RT1 was indeed influenced by compatibility with both S2a and R2. Performance was fastest in Task 1 for trials where the theoretical response to S2a and the executed response to S2b, (i.e., R2) were both compatible or both incompatible with R1 (black lines in the left panel of Fig. 3), and slower for trials with mixed Task 2-to-Task 1 compatibility (where the response to only one of the Task 2 stimuli was compatible with R1, the response associated with either S2a or R2, but not both [gray lines in the left panel of Fig. 3]). These observations were confirmed by the simple main effects: When R1 and R2 were compatible (solid lines in the left panel of

Fig. 3), S2a-R1 compatible trials were faster (*M* = 693.00, *SD* = 146.60) than S2a-R1 incompatible trials (*M* = 710.70, *SD* = 152.52), *t*(18) = -4.35, *p* < .001; however, when R1 and R2 were incompatible (dashed lines), the reverse was true (S2a-R1 compatible, *M* = 716.04, *SD* = 156.23; S2a-R1 incompatible, *M* = 699.76, *SD* = 150.51), *t*(18), = 3.13, *p* = .006. Thus, despite the fact that participants did not execute a response to the distractor S2a, it still had an influence on Task 1 processing through its interaction with R1-R2 compatibility. Additionally, there was some speeding of RT with increasing SOA, *F*(3, 54) = 19.76, *MSE* = 14,378.10, *p* < .001.

Task 2 Reaction Time. Response compatibility effects were also observed in Task 2. Trials in which both the distractor (S2a) and target (S2b) colored squares signaled the same response for Task 2 (i.e., S2a-R2 compatible trials; black lines in the right panel of Fig. 3) were performed faster than incompatible trials (gray lines), *F*(1, 18) = 75.02, *MSE* = 2,619.66, *p* < .001. This strong effect of S2a-R2 compatibility was underadditive with SOA, *F*(3, 54) = 6.63, *MSE* = 1,447.95, *p* = .001. Paired t-tests indicated that S2a-R2 compatible trials were significantly faster than incompatible trials at each SOA, all *t*s > 3.15. S2a-R2 compatibility also interacted with R1-R2 compatibility, *F*(1, 18) = 6.31, *MSE* = 2,259.96, *p* = .022, such that the S2a-R2 compatibility effect was larger when R1 and R2 were compatible (solid lines in the right panel of Fig. 3) [65 ms, *t*(18) = 8.49, *p* < .001], relative to when R1 and R2 were incompatible (dashed lines in the right panel of Fig. 3) [37 ms, *t*(18) = 4.42, *p* < .001]. Finally, consistent with typical PRP results, Task 2 RT decreased significantly with increasing SOA, *F*(3, 54) = 173.75, *MSE* = 5,736.35, *p* < .001, with a slope approaching -1 across conditions at short SOAs.

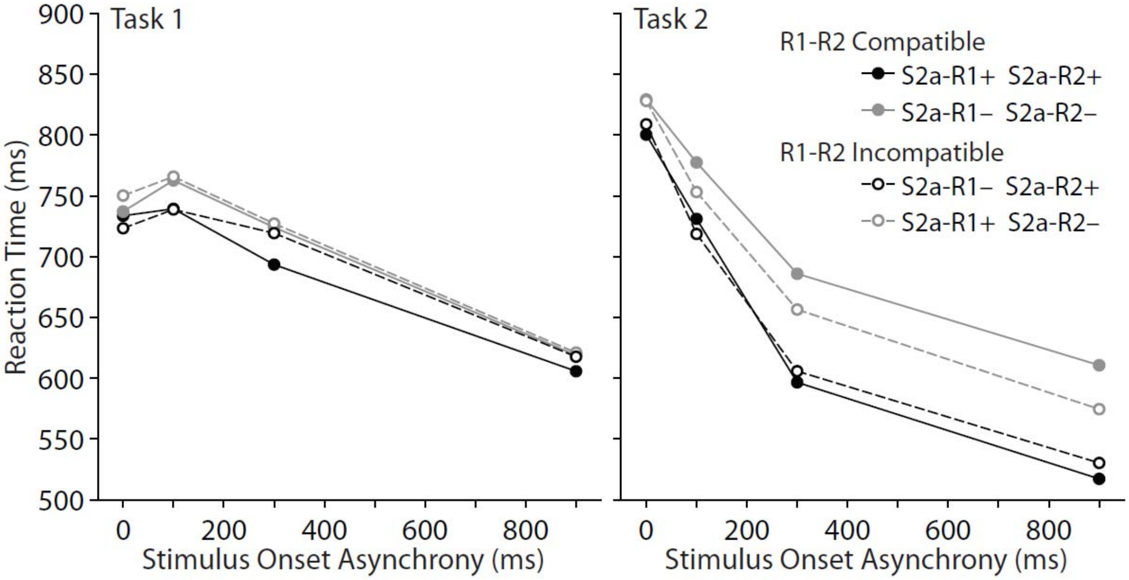

Fig. 3 Mean reaction time data for correct trials in Experiment 1. Data are divided by response compatibility relationships between executed responses in both tasks (R1-R2), and the S2a-related response compatibility relations (compatible, “+”; incompatible “-“) with the responses to Task 1 (S2a-R1) and Task 2 (S2a-R2). Note that for R1-R2 compatible trials, the S2a compatibility relations must be the same for both tasks (e.g., S2a must be either compatible with both R1 and R2 or incompatible with both). For R1-R2 incompatible trials, the S2a relations must differ across tasks (e.g., if S2a is compatible with R2, it must be incompatible with R1, and vice versa). Task 1 data are discussed predominantly in terms of R1-R2 and S2a-R1 compatibility, while analysis of Task 2 data focuses on R1-R2 and S2a-R2 compatibility. Critical S2a-R2 compatibility effects are represented by black (compatible) versus gray (incompatible) lines for both Task 1 and Task 2.

Errors. Task 1 and Task 2 error rate data are presented in Table 1. In general, there were very few errors committed on Task 1, or on both tasks in the same trial, whereas over 80% of all errors were committed on Task 2 following correct Task 1 performance. There were no significant effects involving Task 1 errors. Task 2 error data were largely consistent with the RT data. Performance was more accurate on compatible, relative to incompatible, S2a-R2 trials, $F(1, 18) = 21.01$, $MSE = .005$, $p < .001$. A main effect of R1-R2 compatibility demonstrated less accurate performance for compatible than for incompatible trials, *F*(1, 18) = 5.27, *MSE* =.006, *p* = .034. These two main effects were modified by an interaction between these factors, *F*(1, 18) = 7.87, *MSE* = .002, *p* = .012. Paired t-tests of simple main effects demonstrated that the effect of S2a-R2 compatibility was significant when R1 and R2 were compatible, *t*(18) = 6.34, *p* < .001, and marginally significant when R1 and R2 were incompatible, *t*(18) = 2.05, *p* = .056.

Table 1 Mean error rate (% Error) and standard error of the mean (*SEM*) for each task in Experiment 1

SOA			0		100		300		900	
			% Error	*SEM*	% Error	*SEM*	% Error	*SEM*	% Error	*SEM*
Task 1										
	R1-R2+	S2a-R1+	1.51	0.00	1.53	0.00	0.84	0.00	1.05	0.00
		S2a-R1-	0.99	0.01	1.06	0.00	0.84	0.00	0.17	0.00
	R1-R2-	S2a-R1+	1.55	0.01	1.01	0.01	1.59	0.01	0.58	0.00
		S2a-R1-	1.21	0.00	1.68	0.01	0.33	0.00	1.17	0.00
Task 2										
	R1-R2+	S2a-R2+	4.37	0.01	5.04	0.01	2.18	0.01	4.06	0.01
		S2a-R2-	8.42	0.01	9.67	0.01	10.59	0.02	7.50	0.02
	R1-R2-	S2a-R2+	4.88	0.01	3.23	0.01	2.83	0.01	2.62	0.01
		S2a-R2-	5.44	0.02	5.73	0.02	5.62	0.02	5.61	0.02

Note. Task 1 data are divided by response compatibility relationships (compatible, “+”; incompatible “-“) on overt Task 1 performance from the S2b-related overt Task 2 response (R1-R2) and S2a-related response information (S2a-R1), and stimulus onset asynchrony (SOA). Task 2 data are divided by the response compatibility relationships on overt Task 2 performance from the S1-related overt Task 1 response (R1-R2) and S2a-related response information (S2a-R2), and SOA. The Task 1 error rates presented are independent of Task 2 performance, while Task 2 error rates are those observed after accurate Task 1 performance.

Additional Analysis of S2a-R2 Effects at Short SOAs. Adjusted RT2 measures for each condition in Experiment 1 are displayed in the top panel of Fig. 4. The analysis of RT2 minus RT1 data revealed a pattern of data quite similar to that observed in the original RT2 scores. This included a main effect of SOA, *F*(1, 18) = 179.34, *MSE* =

1,608.91, $p < .001$, demonstrating that there was a larger difference between RT2 and RT1 at the 0-ms SOA as compared with the 100-ms SOA, indicative of a typical PRP effect. Critically, we still observed a main effect of S2a-R2 compatibility, $F(1, 18) = 11.13$, $MSE = 496.59$, $p = .004$, where S2a-R2 compatible trials (black lines in the top panel of Fig. 4) were faster than incompatible trials (gray lines) across both SOAs, with no interaction of S2a-R2 and SOA, $F(1,18) = 0.90$. While there was no main effect of R1-R2 compatibility, $F(1, 18) = 1.40$, $p = .252$, R1-R2 compatibility was observed to interact with S2a-R2 compatibility, $F(1, 18) = 6.64$, $MSE = 845.83$, $p = .019$. Analysis of simple effects showed that the effect of S2a-R2 compatibility was significant when R1 and R2 were compatible (solid lines) [24 ms, $t(18) = 3.92$, $p = .001$], but not when R1 and R2 were incompatible (dashed lines) [0 ms, $t(18) = 0.02$, $p = .986$]. Additionally, observed differences in R1-R2 compatibility over SOA were also significant, $F(1, 18) = 5.05$, $MSE = 902.71$, $p = .037$, because at the 100-ms SOA only, R1-R2 compatible trials were slower than incompatible trials, $t(18) = 2.93$, $p = .009$. The three-way interaction was not significant, $F(1, 18) = 1.24$, $p = .281$. This analysis suggests that when the responses made to each task were compatible, response information from S2a directly influenced RT2. However, when R1 and R2 were incompatible, the observed effect of S2a on RT2 was indirectly propagated from Task 1 via locus of slack mechanisms at short SOAs.

Discussion

The results of Experiment 1 demonstrate Task 2 to Task 1 response priming, replicating similar effects found by Hommel (1998), Watter and Logan (2006), Miller (2006) and others. This backward response priming effect on RT1 was demonstrated for

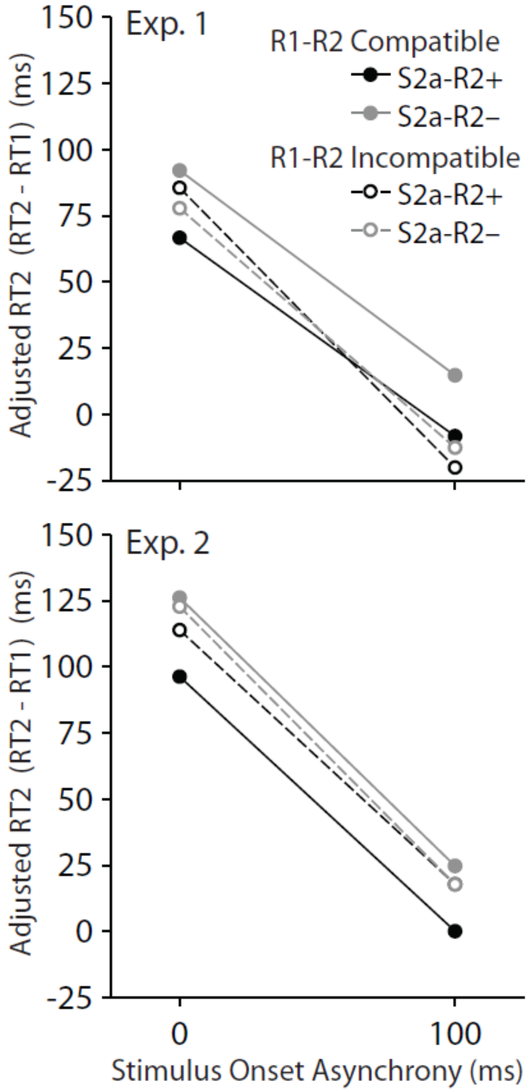

Fig. 4 Mean adjusted Task 2 reaction time (RT) data for correct trials at short SOAs for Experiments 1 and 2. Task 1 RT was subtracted from Task 2 RT for each trial, in order to control for any indirect effects from Task 1 pre-bottleneck or bottleneck stages propagating onto Task 2 RT. Both experiments demonstrate significant S2a-R2 compatibility effects (compatible, "+", black lines; incompatible, "-", gray lines) persisting in these adjusted RT2 scores, for trials in which R1 and R2 are compatible. This suggests S2a-related response information persists across the response selection bottleneck to directly influence overt Task 2 performance for response compatible but not response incompatible trials, in both bivalent (Experiment 1) and univalent (Experiment 2) response situations.

response information arising from the target S2b, and importantly also for response information from the transient distractor S2a, as demonstrated by the interaction of R1-R2 compatibility effects and S2a-R1 compatibility effects. This suggests that response information was computed for S2a in parallel with Task 1 performance, even though this stimulus was not predictive of the eventual Task 2 response and did not require a response itself. We suggest that under these conditions, and with experimental instructions prioritizing Task 1 performance, participants were unlikely to try to make strategic use of the transient S2a stimulus.

Task 1 performance was observed to be slower for trials with short SOAs when S2a and S2b were visible during Task 1 processing. This slowing could be indicative of parallel response selection (Navon & Miller, 2002; Tombu & Jolicoeur, 2003), or simply indicate that participants were distracted, either by the color change or by the mere presence of another stimulus on the screen while they performed Task 1. There is little evidence to suggest that participants were strategically grouping their responses at short SOAs, since interresponse intervals (IRIs) averaged 284 ms over these trials, and only 13% of those trials had an IRI less than 150 ms. Omitting these trials from the adjusted RT2 analysis did not change the pattern of results.

We note that the RT1 data also show an interesting and initially counterintuitive interaction with respect to mixtures of response compatibility. Combinations of RT compatibility effects show relatively fast responding not only for cases where both relationships are response compatible, but also for cases where both relationships are incompatible. Cases with a mixture of one compatible and one incompatible relationship typically show greater RT costs. These kinds of "mixed compatibility" costs have been previously observed in similar studies by the present authors using PRP tasks (e.g., Thomson et al., 2010; Watter & Logan, 2006). These effects are explored more fully in other work (e.g., Hommel's [2004, 2007] work on event files and partial match effects), and we refer the reader there for further explanation. It is worth noting, however, that for our present analysis, trials that were assessed as fully compatible or fully incompatible and produced the fastest responses in Task 1 are also by definition S2a-R2 compatible trials. The slower mixed compatibility trials are, in fact, trials where S2a and S2b are incompatible in Task 2 (for example, if the responses associated with S1 and S2a are compatible but R1 and R2 are incompatible, then S2a and R2 must also be incompatible). Schubert et al. (2008) analyzed their Task 1 data according to these Task 2 compatibility relationships and observed an effect of S2a-R2 compatibility in Task 1. It is possible that S2a-R2 compatibility itself has an influence on the length of the response selection stage at short SOAs in Task 1, independently of the partial match effects described above (see Schubert et al.'s, 2008, discussion of Experiment 2 for a proposed mechanism for this manner of cross talk). The presence of this cross talk is not the focus of our analysis; however, it does further necessitate the subsequent analysis of adjusted RT2 scores, as is discussed below.

Central to our investigation is whether response information generated from S2a in parallel with attended Task 1 performance persisted across the bottleneck, surviving the attentional switch from Task 1 to Task 2 performance, to directly influence RT2. We observed a compatibility effect in our initial analysis of RT2 between the associated (but unmade) response to S2a and the attended, S2b-driven Task 2 response R2 (S2a-R2 compatibility). However, it is possible that this effect may have been due to the indirect influence of either S2a-R1 or S2a-R2 compatibility effects at prebottleneck or bottleneck stages in RT1, influencing RT2 at short SOAs via locus of slack effects. Schubert et al. (2008) argued that S2a influences on RT2 operated via this indirect influence and that S2a-related response information did not survive across the bottleneck to directly influence Task 2 performance.

To determine whether this was the case in our study, we conducted an additional analysis on RT2 minus RT1 difference scores, calculated for every trial at the shortest two SOAs, where we observed a strong PRP effect. Adjusting RT2 in this way should remove any effects influencing Task 1 prebottleneck or bottleneck stages, so that any cross talk or compatibility effects from Task 2 on Task 1 that propagate via locus of slack onto Task 2 RTs are removed from the resultant adjusted RT2 scores. If S2a exerted an influence on Task 2 only via this indirect mechanism, the S2a-R2 compatibility effect should disappear in this analysis. We still observe a strong influence of S2a-R2 compatibility on these adjusted Task 2 RT scores, but only when R1 and R2 were also compatible. When the responses across tasks were incompatible, the adjusted RT2 scores do not demonstrate the S2a-R2 compatibility effect.

One possible explanation is that the bypass of S2a information across the bottleneck is robust only within a single response effector (in this case, the same finger). When participants use one finger to respond to Task 1 and a different finger to respond to Task 2, perhaps any currently activated response information is reset when it becomes apparent that the second task requires a response that is different from the one executed previously—including accumulated S2a response information, regardless of its compatibility with R2. This is consistent with the fact that Schubert et al. (2008) did not find evidence for the bypass model when participants responded to each task with a different hand, precluding response repetition. We address this issue in Experiment 2.

The results of Experiment 1 still have important implications for information continuity across the RSB, suggesting that S2a-R2 compatibility effects are not exclusively due to indirect effects via Task 1. Taken together with our previous analysis that demonstrated an effect of S2a response information on Task 1, it appears that response information for S2a is generated in parallel with attended Task 1 performance and, in certain situations, persists to at least some degree across the RSB to prime the overt response to the target stimulus in Task 2.

The S2a-R2 response compatibility effect in Task 2 from our main RT analysis was observed to be underadditive with SOA. Interpreted from a strict locus of slack perspective (e.g., Pashler, 1994), our data would suggest that the computation of response information can occur in parallel for both tasks in a PRP paradigm, prior to the observed central bottleneck on explicit Task 2 performance. We consider the implications of these data more fully under locus of slack and alternative models below, in the General Discussion section.

Experiment 2

In Experiment 1, we demonstrated that early response information for Task 2 can indeed bypass the bottleneck to influence later Task 2 response selection processing.

These findings are in contrast to those of Schubert et al. (2008), who found only indirect propagation across the RSB. One important difference between these studies is that in our present Experiment 1, responses were performed with the same hand, using the same response keys across tasks. Using this bivalent design, we observed a bypass effect only when the responses were compatible across tasks, resulting in response repetition. It is possible that on response alternation trials, any prior response activation is ignored to prevent response perseveration. This would result in any accumulated response information for S2a being discarded between tasks. Since a two-handed, univalent design always results in response alternations between tasks, it seems plausible that the bivalent nature of our Experiment 1 design was the reason we found evidence in support of the bypass model when Schubert et al., with their univalent design, did not.

In order to test this possibility, we conducted a second experiment that replicated the univalent, two-handed response mapping used by Schubert et al. (2008). Participants performed the same tasks as in Experiment 1, but this time participants responded to S1 with the index or middle finger of their right or left hand and responded to S2b with the index or middle finger of the opposite hand. If the bypass effect depends on response repetition and this is the reason that our results differ from those of Schubert et al., we should not observe any evidence of S2a information continuity across the RSB in Experiment 2. Instead we should replicate the findings of Schubert et al. and observe that the only influence of early Task 2 response information on Task 2 performance is mediated indirectly by cross talk via Task 1. Specifically, the S2a-R2 compatibility effect should have the same magnitude in Task 1 and Task 2, regardless of R1-R2 compatibility, and therefore there should be no effect of S2a-R2 compatibility in the adjusted RT2 scores. Alternatively, observing evidence of direct S2a-R2 influences on RT2 as in Experiment 1 would indicate that response information for Task 2 can bypass the bottleneck even when the responses are not identical across tasks.

Method

Participants. Twenty-eight undergraduate students (13 females) enrolled in psychology courses at McMaster University participated in the experiment in exchange for partial course credit. All had normal or corrected-to-normal vision, and all but 2 were right handed.

Apparatus, Stimuli, and Procedure. The apparatus, stimuli, and procedure were identical to those in the previous experiment, except for the following changes. (1) A subset of participants completed the experiment on an HP Pro 3130 computer with a Samsung SyncMaster B2240 monitor. The same experimental software was used on both computers, and the stimuli were the same physical size on both monitors. (2) Participants made separate responses to each task using a different hand. Half of the participants responded to the letter task using the middle and index finger of their left hand on two response buttons located on the left side of the keyboard, while the other half responded to the letter task using the index and middle finger of their right hand on response buttons on the right side of the keyboard. Participants used the index and middle finger of the opposite hand to respond to the color task. Stimulus-response mapping was counterbalanced within each task. Since participants made responses to each task with a separate hand, we defined R1-R2 compatible trials as those that required the same finger across tasks (i.e., both index fingers or both middle fingers) and R1-R2 incompatible trials as those that required a different finger for each task (e.g., left middle finger and right index finger).[3]

Results

Two participants were excluded from the analysis because they did not meet the accuracy criterion of 70% correct trials. A third participant was excluded because he was unable to follow instructions to prioritize Task 1: Consistent response grouping resulted in very long RT1s in the 900-ms SOA condition, leaving no more than six trials per condition under our RT trimming criteria. RT trimming for the remaining 25 participants removed an average of 3.6% of trials from each participant's data set. Mean RTs for correct responses are displayed in Fig. 5.

Task 1 Reaction Time. Observed variability in Task 1 RTs across SOAs produced a main effect of this variable, $F(3, 72) = 7.63$, $MSE = 12{,}263.07$, $p < .001$. More important, the interaction of S2a-R1 and R1-R2 compatibility approached significance, $F(1, 24) = 3.03$, $MSE = 2{,}660.78$, $p = .094$, and there was a significant three-way interaction involving SOA, S2a-R1 compatibility, and R1-R2 compatibility, $F(3, 72) = 3.24$, $MSE = 1{,}900.73$, $p = .027$. We therefore analyzed the two compatibility manipulations at each level of SOA and found only a significant interaction of S2a-R1 and R1-R2 compatibility at the 100-ms SOA, $F(1, 24) = 21.67$, $MSE = 851.24$, $p < .001$.

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[3] Note that in Schubert et al. (2008), R1-R2 compatibility was defined using spatially compatible fingers across tasks (left-middle/right-index fingers and left-index/right-middle fingers were compatible). This was important for them because they used a spatial Task 2 (directional arrows). The stimuli in the present experiment do not have such strong spatial associations, and we predicted finger identity would be a stronger source of compatibility than spatial compatibility in our tasks (see Watter & Logan, 2006, for another demonstration of R1-R2 compatibility based on compatible fingers rather than spatial compatibility across hands).

Decomposing this interaction further revealed a pattern similar to that found in Experiment 1: Performance at this SOA was faster for trials in which the responses associated with both S2a and R2 were either compatible or incompatible with R1 than for trials with mixed compatibility. These observations are supported by the simple main effects. When R1 and R2 were compatible (solid lines in left panel of Fig. 5), S2a-R1 compatible trials were marginally faster (*M* = 746.57, *SD* = 137.37) than S2a-R1 incompatible trials (*M* = 762.89, *SD* = 148.04), *t*(24) = 1.99, *p* = .058. However, when R1 and R2 were incompatible (dashed lines), S2a-R1 incompatible trials were faster (*M* = 736.89, *SD* = 138.43) than S2a-R1 compatible trials (*M* = 774.89, *SD* = 137.03), *t*(24) = -3.43, *p* = .002. Again, this is analogous to the interpretation of a main effect of S2a-R2 compatibility (black vs. gray lines) producing faster RTs in Task 1, at least at the 100-ms SOA.

Task 2 Reaction Time. In Task 2, we again observed a main effect of S2a-R2 compatibility, where compatible trials (black lines in the right panel of Fig. 5) were performed significantly faster than incompatible trials (gray lines), *F*(1, 24) = 103.66, *MSE* = 2,953.69, *p* < .001. This effect of compatibility of distractor and target Task 2 stimuli was again underadditive with SOA, *F*(3, 72) = 13.26, *MSE* = 1,463.39, *p* < .001. Paired samples *t*-tests indicated that the effect of S2a-R2 compatibility was significant at each SOA (all *t*s > 4.61). In addition, the effect of R1-R2 response compatibility across tasks was marginally significant, *F*(1, 24) = 3.60, *MSE* = 1,533.81, *p* = .070, with response compatible trials (solid lines in the right panel of Fig. 5) faster than response

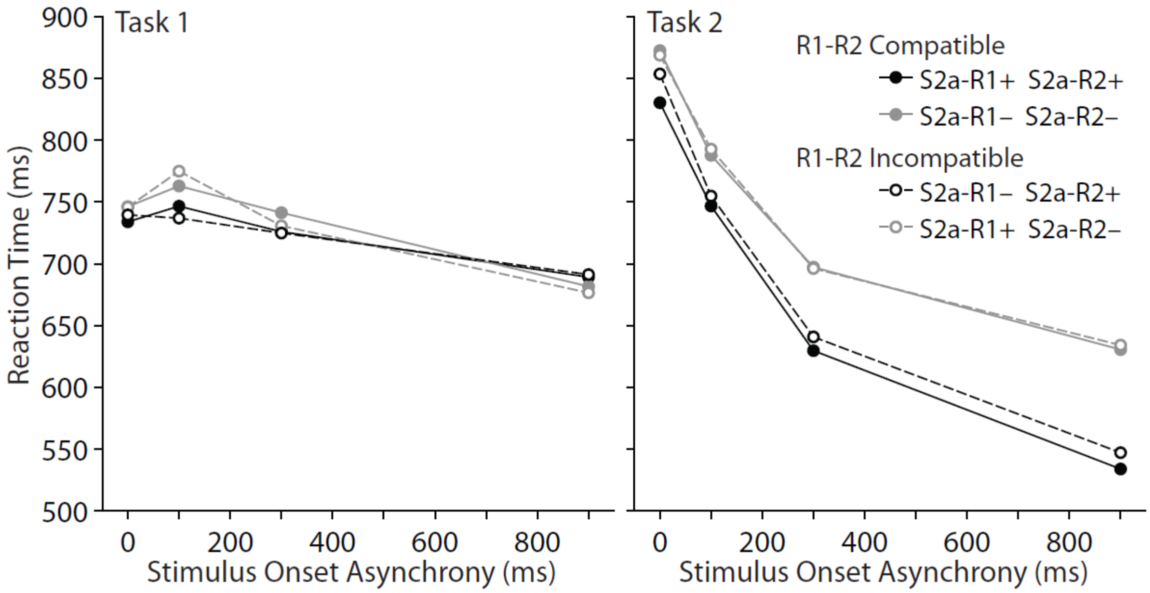

Fig. 5 Mean reaction time (RT) data for correct trials in Experiment 2. As in Figure 3 (Experiment 1), data are divided by response compatibility relationships between executed responses in both tasks (R1-R2), and the S2a-related response compatibility relations (compatible, "+"; incompatible "-") with the responses to Task 1 (S2a-R1) and Task 2 (S2a-R2). Note that for R1-R2 compatible trials, the S2a compatibility relations must be the same for both tasks (e.g., S2a must be either compatible with both R1 and R2 or incompatible with both). For R1-R2 incompatible trials, the S2a relations must differ across tasks (e.g., if S2a is compatible with R2, it must be incompatible with R1, and vice versa). Task 1 data are discussed predominantly in terms of R1-R2 and S2a-R1 compatibility, while analysis of Task 2 data focuses on R1-R2 and S2a-R2 compatibility. Critical S2a-R2 compatibility effects are represented by black (compatible) versus grey (incompatible) lines for both Task 1 and Task 2.

incompatible trials (dashed lines). Consistent with typical PRP data, Task 2 RTs decreased significantly with SOA, $F(3, 72) = 189.07$, $MSE = 7{,}376.63$, $p < .001$.

Errors. Task 1 and Task 2 error data are presented in Table 2. Once again, there were no significant effects involving Task 1 errors. Task 2 accuracy data demonstrated that participants made fewer errors when S2a and R2 were compatible, $F(1, 24) = 29.90$, $MSE = 0.009$, $p < .001$, with this S2a-R2 effect more prominent at longer SOAs, $F(3, 72) = 14.10$, $MSE = 0.003$, $p < .001$. Finally, the interaction between R1-R2 compatibility and

SOA approached significance, *F*(3,72) = 2.47, *MSE* = .002, *p* = .069. This describes the pattern that R1-R2 compatible trials were numerically more accurate than R1-R2 incompatible trials at all but the 900-ms SOA.

Table 2 Mean error rate (% Error) and standard error of the mean (*SEM*) for each task in Experiment 2.

SOA			0		100		300		900	
			% Error	*SEM*	% Error	*SEM*	% Error	*SEM*	% Error	*SEM*
Task 1										
	R1-R2+	S2a-R1+	3.31	0.01	3.54	0.01	2.24	0.01	2.32	0.01
		S2a-R1-	3.11	0.01	2.33	0.01	1.83	0.01	2.54	0.01
	R1-R2-	S2a-R1+	2.18	0.01	3.13	0.01	3.23	0.01	3.03	0.01
		S2a-R1-	3.86	0.01	3.32	0.01	2.54	0.01	2.61	0.01
Task 2										
	R1-R2+	S2a-R2+	8.58	0.02	6.90	0.02	4.56	0.01	4.81	0.01
		S2a-R2-	9.26	0.02	9.10	0.02	14.35	0.02	12.67	0.02
	R1-R2-	S2a-R2+	8.28	0.02	11.07	0.02	8.17	0.02	4.51	0.01
		S2a-R2-	11.24	0.02	10.40	0.02	14.99	0.03	11.94	0.02

Note. Task 1 data are divided by response compatibility relationships (compatible, "+"; incompatible "-") on overt Task 1 performance from the S2b-related overt Task 2 response (R1-R2) and S2a-related response information (S2a-R1), and stimulus onset asynchrony (SOA). Task 2 data are divided by the response compatibility relationships on overt Task 2 performance from the S1-related overt Task 1 response (R1-R2) and S2a-related response information (S2a-R2), and SOA. The Task 1 error rates presented are independent of Task 2 performance, while Task 2 error rates are those observed after accurate Task 1 performance.

Additional Analysis of S2a-R2 Effects at Short SOAs. We again calculated the difference between RT1 and RT2 for correct trials at the shortest two SOAs and conducted an analysis on these adjusted RT2 scores to investigate whether there was any influence of S2a on R2 independently of propagation of pre-bottleneck or bottleneck RT1 compatibility effects via locus of slack onto RT2. These adjusted RT2 data for Experiment 2 are shown in the right hand panel of Fig. 4. Once again, we observed a main effect of SOA, *F*(1, 24) = 552.20, *MSE* = 899.49, *p* < .001, indicating that the difference between RT1 and RT2 was greater at the 0-ms SOA than at the 100-ms SOA. Critically, we again observed a main effect of S2a-R2 compatibility in the adjusted RT2 data, $F(1, 24) = 8.55$, $MSE = 1{,}465.79$, $p = .007$, and this effect did not interact with SOA ($F < 1$). The S2a-R2 compatibility effect did interact with R1-R2 compatibility, $F(1, 24) = 6.72$, $MSE = 970.48$, $p = .016$. Analysis of the simple main effects demonstrated that the S2a-R2 compatibility effect (black vs. gray lines in the right panel of Fig. 4) was significant when R1 and R2 were compatible (solid lines) [18 ms, $t(24) = 4.58$, $p < .001$], but not when R1 and R2 were incompatible (dashed lines) [-5 ms, $t(24) = .56$, $p = .58$].

Discussion

The results of Experiment 2 largely replicated those of Experiment 1. Task 1 responses were influenced by both R2- and S2a-related response information (although this effect reached significance only at the 100-ms SOA), and for RT2, we observed a strong influence of S2a-R2 compatibility that was underadditive with SOA. When we examined RT2 minus RT1 difference scores to assess whether S2a-R2 effects on RT2 were more than an indirect influence of effects propagating from RT1, we again found a significant effect of S2a-R2 compatibility on adjusted RT2 scores. As in Experiment 1, this effect was present only when R1 and R2 were compatible. This suggests that when responses were compatible across tasks, S2a-related response information was available to directly influence RT2 following the attentional shift from Task 1 to Task 2 performance.

These results suggest that early S2a response information can bypass the bottleneck even when there is no physical response repetition, because in this experiment, the effect was observed across different response hands. Our findings here are extremely similar to those in Experiment1 and differ from those of Schubert et al. (2008), who did not observe information continuity across the bottleneck with a univalent design. It is worth noting that in this experiment, we did not observe an interaction of R1-R2 and S2a-R2 compatibility in our initial Task 2 analysis (Fig. 5). This replicates the results of Schubert et al., who found that these effects were independent and additive in Task 2. Despite this, we still observe an S2a-R2 compatibility effect in our adjusted RT2 data. Notably, this bypass effect observed with our univalent design is again present only for R1-R2 compatible trials—in the present experiment, when responses are made with different effectors that are conceptually response compatible between tasks (based on finger identity, right-index–left-index or right-middle–left-middle). Taken together, these results might suggest a variable response resetting mechanism that suppresses Task 2 response information computed in parallel with Task 1 (and potentially Task 1 response information also) when responses are not compatible across tasks but does not completely suppress early response activation when responses are conceptually compatible. This possibility is explored further in the General Discussion section.

General Discussion

Early Task 2 Response Activation Can Persist Across the Bottleneck

Despite several accounts of parallel response selection processes in dual task paradigms, such studies have still exhibited substantial RT costs for Task 2 performance at short SOAs (Hommel, 1998; Miller, 2006; Miller & Alderton, 2006; Thomson et al., 2010; Watter & Logan, 2006). A number of authors have proposed models of dual-task performance that involve varying degrees of parallel computation of response information for both tasks at once, yet also involve serial final response selection prior to overt responding to each task (e.g., Hommel, 1998; Logan & Gordon, 2001). An alternative possibility, discussed by Logan and Gordon and Watter and Logan, is that any residual response information present following the eventual selection of a response for Task 1 might be discarded or suppressed in order to reduce interference on Task 2 performance. In this case, with sufficiently great suppression of any response information present at the end of Task 1 response selection, the overt engagement of response selection for Task 2 may essentially proceed with no persistent or residual activation from earlier in a trial, including an absence of any Task 2 response information that was generated in parallel with overt Task 1 response selection. In this case, the observation of Task 2 response compatibility effects on Task 1 performance would not necessarily violate the spirit of the RSB theory (Pashler, 1994; Pashler & Johnston, 1998); in an informational sense, a strict bottleneck could be considered to be intact, in that Task 2 response selection would have to begin from scratch following the completion of Task 1 response selection.

In the present study, we set out to test the extent to which early Task 2 response information generated in parallel with attended Task 1 response selection could persist over the duration of a dual-task trial, to influence the eventual overt performance of Task 2. Two experiments employed a stimulus substitution technique in Task 2 to assess response priming from early unattended Task 2 response information on participants' eventual Task 2 responses. In both experiments, we found an influence of response information generated from both our early transient S2a stimulus and the task-relevant S2b stimulus on Task 1 performance that replicated similar findings of backward compatibility observed by Hommel (1998), Miller (2006), Miller and Alderton (2006), Thomson et al., (2010), and Watter and Logan (2006).

Critically, in both experiments, we demonstrated a clear influence of S2a-related response information on overt Task 2 performance at short SOAs, independent of any indirect influences from Task 1 prebottleneck or bottleneck processing stages propagating onto Task 2. We suggest that this S2a-R2 effect represents direct evidence of early Task 2 response information generated in parallel with Task 1 response selection persisting across the attentional shift from Task 1 to Task 2 performance, bypassing the RSB and directly influencing overt response selection for Task 2. As an important boundary condition, we observed this effect only when Task 1 and Task 2 responses were compatible. In Experiment 1, this response compatibility existed as a repetition in Task 2 of the same physical response effector as that from Task 1 (bivalent; e.g., right-index–right-index); in Experiment 2, response compatibility was instantiated as responding with the same finger identity on the opposite hand for Task 2 as was used for Task 1 (univalent; e.g., right-index–left-index). When the responses were not compatible across tasks (e.g., right-index–right-middle in Experiment 1, right-index–left-middle in Experiment 2), we did not observe any influence of early Task 2 response information on overt Task 2 performance, beyond an effect that was indirectly propagated onto Task 2 via cross talk with Task 1 prebottleneck or bottleneck stages.

We contrast our findings with those of Schubert et al. (2008), who found only indirect effects of S2a-R2 compatibility on Task 2 performance (described there as congruency between the two Task 2 stimuli), mediated via compatibility effects on Task1 with propagation to RT2. Our data provide the first evidence supporting the bypass model, where early Task 2 response activation contributes directly to later, attended Task 2 response selection.

Our demonstration of equivalent S2a-related response compatibility effects across bivalent (Experiment 1) and univalent (Experiment 2) response mapping situations suggests that the locus of these effects (and backward response compatibility effects in general) is likely at the level of central and abstract response code representation, versus later response execution. The observation of response compatibility effects under differing R1-R2 compatibility definitions for the present study versus Schubert et al. (2008) is also consistent with this idea. Schubert et al. defined response compatibility by spatial correspondence, where we defined it as finger identity. Our tasks were explicitly described to participants in this way (describing response mappings as “index” or “middle” for particular stimuli); in contrast, many of Schubert et al.’s tasks used choice responding to spatial cues, and we speculate that there participants may have been instructed relative to “left versus right” responses within a hand, as opposed to finger identity. We note above (see footnote 2) that a number of prior studies have used both of these opposing versions of response compatibility (identity vs. spatial correspondence) and have generally found their own assumptions of compatibility confirmed. We suggest that our data combined with those in Schubert et al. demonstrate a somewhat flexible alignment of response compatibility relationships, based on task rules and the conceptualization of response features. We suggest that these observations provide further converging support for the notion of response compatibility effects influencing centrally represented response codes, as opposed to later response execution processes.

Variable Resetting of Response Information between Tasks

We are particularly interested in the observation that Task 1 to Task 2 (R1-R2) response compatibility appears to be a prerequisite for information continuity across the bottleneck for Task 2. We suggest that these data may represent the action of a response information resetting mechanism somewhat akin to the theoretical proposal of Logan and Gordon (2001), although here with a variable sensitivity depending on the degree of response compatibility between tasks.

Logan and Gordon (2001) and Watter and Logan (2006) suggested that while suppression of response information following Task 1 response selection would be important to prevent response perseveration and interference and allow for fast and accurate serial dual-task performance, the degree of suppression required to achieve this might be substantially less than 100%. This would suggest any potential informational bottleneck instantiated via response suppression might be substantially leaky. Framed in this way, our current S2a-R2 compatibility data suggest an essentially complete informational bottleneck for response (R1-R2) incompatible trials but suggest that this response suppression is incomplete when Task 1 and Task 2 trials have compatible responses.

The question of how response compatibility might influence the degree of response information suppression on a trial-to-trial basis is a difficult one; in Logan and Gordon's (2001) treatment, response information suppression is treated as a global performance parameter. One possibility is that participants might become sensitive to the degree of response incompatibility experienced on each trial. At short SOAs, this interference would be substantially experienced prior to the completion of Task 1 response selection, from response information generated from Task 2 stimuli. The degree of conflict experienced in Task 1 response selection could directly drive the strength or extent of a subsequent response inhibition mechanism. In this situation, participants may learn (or put another way, this system may become tuned over performance) so that response-compatible trials generating minimal response conflict on Task 1 response selection elicit relatively less response information suppression, in turn allowing some degree of response facilitation on response-compatible trials. This possibility may fit well with current literatures in response conflict and error monitoring (e.g., Yeung, Botvinick, & Cohen, 2004) and may predict other correlates (such as anterior cingulate involvement), if true.

An alternative mechanism for this same effect may not require that response compatibility information directly drive response information suppression on a given trial. Instead, in an episodic account, particular stimulus pairs may become associated with the experience of relatively high or low degrees of response interference. Changes in the degree of response suppression would initially occur only after these experiences, but over time, these differing suppression states may be elicited directly from particular stimulus pairs prior to (or at least in parallel with) the activation and potential interference of response information for both tasks. This account is conceptually very similar to work by Bugg, Crump, and colleagues (Bugg, Jacoby, & Chanani, 2011; for a review, see Bugg & Crump, 2012) showing rapid automatic contextual control of single-task performance with item-specific proportion congruency manipulations. A related possibility is that response information suppression occurs following a failure of event file integration (Hommel, 2004) on response-incompatible trials. These episodic accounts would predict the development of this variable response information suppression over experience, perhaps dependent on task rule complexity, while in the prior version, we might expect the degree of response information suppression to be immediate and more directly tied to transient activations within particular trials.

Considering all this, we suggest that the detection of direct S2a-R2 influences on RT2 should be considered as a marker for situations where we might expect the influence of other, stronger sources of response information to similarly persist across an informational bottleneck and influence RT2. We include here all response information generated prior to the beginning of Task 2 response selection—not just early Task 2 response activation, but response information from Task 1 also. There are substantial methodological difficulties in separating the direct influence of central Task 1 response information on RT2 from the motoric effects of an already-made R1 response on RT2; distinguishing the relative contributions of response information generated from a typical Task 2 stimulus prior to and during response selection is similarly tricky. Nevertheless, we suggest that these effects might be substantial and are predicted on the basis of the general assumption of response information suppression in serial dual-task performance and our demonstration of this variably permissive informational bottleneck.

Alternative Models of Response Activation and Response Selection

In our demonstration of the direct influence of S2a-related response compatibility on overt Task 2 performance at short SOAs, S2a-R2 compatibility effects were observed to interact underadditively with SOA. Such underadditivity in RT in Task 2 of a PRP paradigm has traditionally been interpreted under the locus of slack logic (Pashler, 1994) as reflecting a task manipulation at a prebottleneck processing stage in Task 2. Framed in this way, our data suggest that the computation of response information may be embodied in a separate processing stage—here termed response activation, following Hommel (1998)—prior to the well-described central bottleneck involved with response selection. This interpretation is represented in the top half of Fig. 6 (panels a1 and a2). The duration of the response activation stage driven by the task-relevant S2b stimulus is relatively shorter when primed by compatible response information from the simultaneous response activation stage driven by the distractor S2a stimulus (S2a-R2+), as compared with a longer duration of response activation for S2b when S2a and S2b are associated with incompatible responses (S2a-R2–). At short SOAs (panel a1), these differences in response activation stage durations have little to no effect on overall S2b-driven Task 2 RT, since the later response selection stage for S2b is delayed until Task 1 response selection has finished. At longer SOAs (panel a2), the difference in S2b response activation stage duration due to compatibility effects from S2a response information have

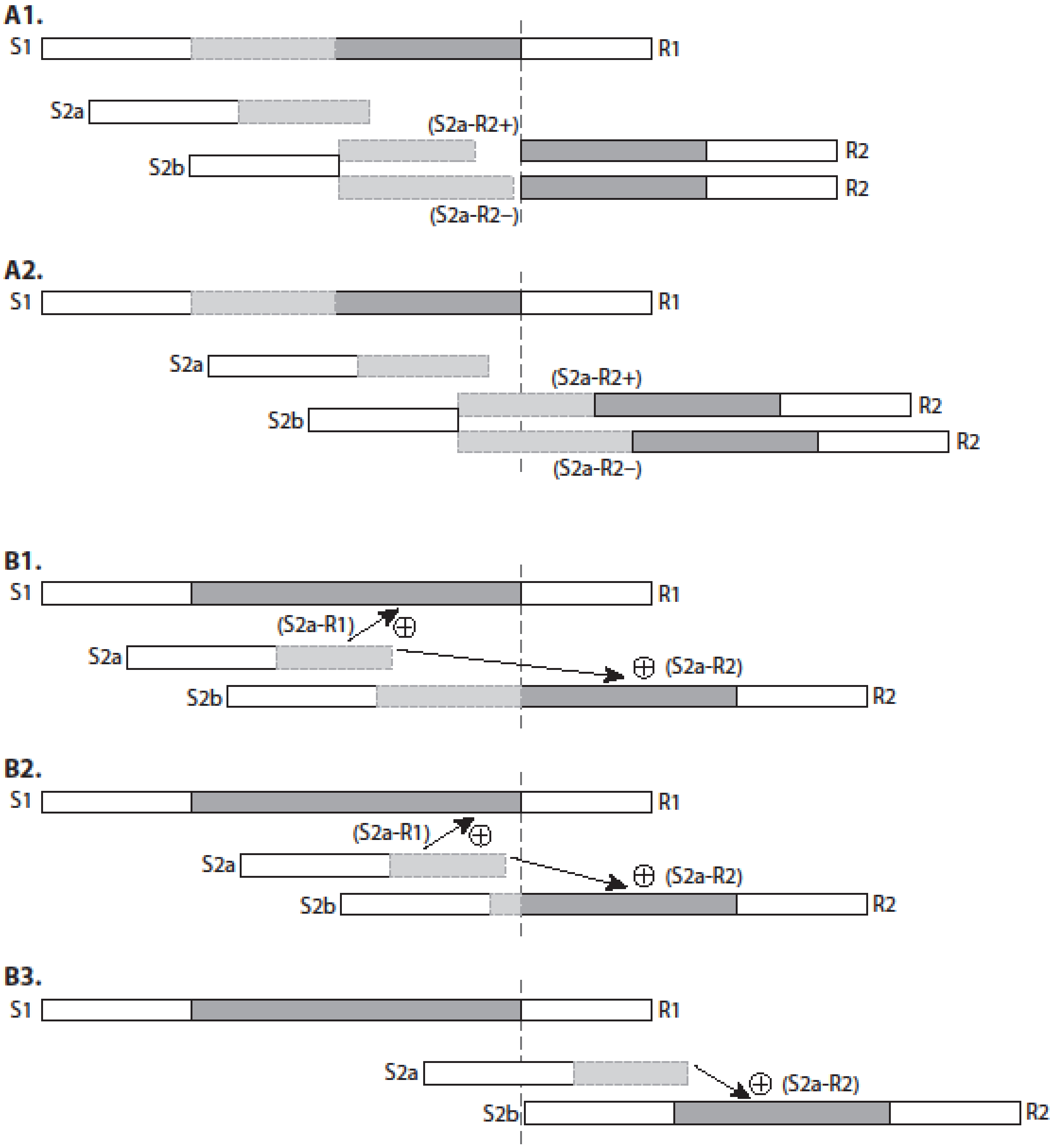

Fig. 6 Alternative models of underadditivity of S2a response compatibility effects on Task 2 performance (S2a-R2 compatibility) with SOA. Dark grey shading indicates the response selection stage; light grey shading indicates response activation. Panels a1 and a2 depict a strict locus of slack interpretation at shorter and longer SOAs respectively. With a short SOA, the variable duration of the main S2b-related Task 2 response activation stage (due to compatibility effects from S2a response activation) is absorbed in

pre-bottleneck slack time, with small or no differences in overall RT between S2a-R2+ (compatible) and S2a-R2– (incompatible) conditions. At a longer SOA, overt response selection stages of Task 1 and Task 2 no longer overlap, and so differences in Task 2 response activation stage durations are fully reflected in overt Task 2 RTs. Panels b1, b2 and b3 represent response priming effects of early parallel response activation from S2a in a non-serially dependent model of response activation, over progressively longer SOAs. Limited S2a-related response activation is increasingly separated in time from overt Task 2 response selection as SOA decreases. This separation could restrict the influence of early S2a response information at shorter, relative to longer, SOAs, leading to an underadditive pattern of S2a-R2 compatibility and SOA in the present study.

a greater influence on final Task 2 RT, since the final response selection stage is no longer delayed by Task 1 response selection.

While this interpretation may be initially appealing, the framing of response activation as a separate processing stage within the locus of slack framework would require a number of strict assumptions, including that response activation and selection processes were serially discrete and computationally independent. Many single-task models of central information processing do not make these assumptions and often make little distinction between the process of computing response information and the selection of a to-be-made response. For example, foundational work by Coles, Gratton, and colleagues (e.g., Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton, Coles & Donchin, 1992; Gratton, Coles, Sirevaag, Eriksen & Donchin, 1988) suggests that while the computation and activation of a response may involve both parallel and focused processing stages, these stages are typically observed to be continuously cascaded, with contextual and strategic factors able to influence the degree to which parallel versus later focused processing stages contribute to determining the final response. Compatible with these ideas, work by Hommel and colleagues (e.g., Hommel, 2004; Hommel, Müsseler, Aschersleben, & Prinz, 2001) and others suggests that with sufficient prior experience, associated response features are automatically and directly activated from episodic memory by related perceptual cues, in the absence of deliberate focused response selection performance. We suggest that these kinds of effects, when embodied in a PRP-like dual-task situation, seem conceptually very similar to the effects of prebottleneck parallel response activation for Task 2 and related response compatibility effects suggested in the present article and elsewhere.

In a similar sense, one can suggest a number of situations where response activation and final response selection processes may have a reciprocal or interactive relationship within a single task. For example, in the present study as previously (e.g., Thomson et al., 2010; Watter & Logan, 2006), early activation of Task 2 response information in parallel with overt Task 1 performance has been suggested to be unattended and automatic, while overt Task 2 performance (following Task 1 response selection) is assumed to be attended and controlled. If we consider unattended Task 2 response activation to operate along the lines of a general competitive information accrual model, (e.g., Nosofsky & Palmeri's [1997] exemplar-based random walk model or a simpler race-style or diffusion-style model), then the time for which this automatic response activation process runs will influence the quality of response activation when overt Task 2 processes begin. Other things being equal, this might predict that when relatively little unattended response activation occurs prior to overt task performance, overt response selection may need to perform relatively more work than when unattended response activation has run for longer. While this issue is difficult to directly assess, the general point is that there is good reason to suspect that automatic response activation and overt response selection processes might be quite interdependent, with reciprocal relationships relative to computation of task responses.

The flexibility of overt response selection to perform more or less response computation, depending on the extent of unattended response activation or the degree of other potential influences (e.g., degrees of interference), is quite distinct from the situation discussed above where a separate response activation stage is incorporated into a locus of slack framework; in that case, response activation and response selection would need to assume serially distinct processing domains—for example computation of response information in response activation and subsequent response gating in response selection.

Redundancy of processing in two sequential stages would also violate the seriality assumptions of the model. For example, having two sequential stages that both generate the same kind of information (e.g., both processes may increment the same response counters) is a very strange situation in terms of serial stage models commonly used in cognitive psychology. Similarly, response activation as a processing stage might be able to run concurrently with overt response selection, akin to various automaticity accounts (e.g., Logan, 1988), where algorithmic and instance-based processes race to produce a response. These characteristics make response activation a very difficult process to fit cleanly into a discrete serial stage model, when the process in question does not have to reach some asymptote of information processing before subsequent processes can begin. While processing stages are in reality likely cascaded and overlapping, most authors take the practical approach of assuming that a serial and discrete model is a sufficient approximation, due to computational and interpretational simplicity.

If dependencies between automatic response activation and attended response selection performance in Task 2 suggest that the serial stage locus of slack logic may be an inappropriate model for interpreting our findings, how should we alternatively interpret the underadditivity with SOA in our Task 2 response priming data? One suggestion is illustrated in the lower half of Fig. 6. The three lower panels illustrate a progression of the general time course of processing of our present design, over shorter through longer SOAs (panels b1–b3), with locus of slack assumptions only regarding the serial dependency of overt central response selection processing. The potential effects of response information generated from the distractor S2a on Task 1 (S2a-R1) and Task 2 (S2a-R2) responses are indicated. In the present set of experiments, S2a was presented for a short and constant period of time (200 ms) prior to being replaced by the main task-relevant S2b stimulus, regardless of SOA. As such, at long SOAs, S2a was presented relatively close in time with overt Task 2 performance; as SOA decreased, overt Task 2 performance was delayed more and more, separating overt Task 2 performance from the initial transient S2a presentation. We suggest that any response activation arising from S2a would likely be time limited or would reach some maximal extent of activation relatively quickly in the course of the trial, especially given the short presentation and replacement with a task-relevant stimulus from the same set. As such, overt Task 2 performance at short SOAs may have been less influenced by S2a response information, due to increased separation in time from the activation of S2a-derived response information, as compared with Task 2 performance at later SOAs. If the S2a distractor had remained onscreen for the duration of the trial, to continue to drive automatic response activation, such an underadditive result may not have been observed.

This argument so far assumes S2a-related response information to be generated in the same fashion at all SOAs, which is probably not the case. We suggest that S2a likely has additional pronounced effects on RT2 as SOA increases, when S2a is present onscreen during overt Task 2 performance following completion of Task 1 response selection, and complicates straightforward comparisons and predictions of S2a effects at early versus late SOAs. Bearing this caveat in mind, we note that the magnitude of our S2a-R2 compatibility effects at short SOAs is approximately one third the size of the S2a-R2 compatibility effect observed at the 900-ms SOA in both experiments. This suggests that while a detectable influence of S2a information might persist across the bottleneck, a majority of the S2a-related response information (or at least a majority of the measured compatibility effect) does not appear to survive to influence RT2. Early Task 2 response activation does appear to directly influence RT2, but the effect may be relatively small as compared with the contribution of overt Task 2 response selection, at least in these kinds of task situations. This said, we focus here on S2a effects because we can distinguish S2a-R2 effects from the effect of producing R2 from the target stimulus S2b. It is possible that potentially much larger direct effects might arise from early Task 2 response activation from the target S2b stimulus, especially considering its continuous availability and task-relevance—although quantifying the degree of response information generated from automatic S2b-R2 activation versus overt S2b-R2 response selection is a more difficult problem.

Alternative Accounts of S2a-R2 Compatibility Effects

Finally, we consider two potential alternative interpretations of our S2a to R2 compatibility effects. One alternative is that instead of representing the effects of response information generated from S2a on R2, these S2a-R2 compatibility effects may represent priming of prebottleneck semantic category representations. By this account, S2a would only facilitate the activation of the semantic category representation of S2b (when compatible), leading to faster Task 2 performance due to a presumably faster or stronger establishment of the S2b category representation, without any direct effect of S2a-related response information on RT2.

Compatibility between semantic category representations in dual-task situations akin to the present general PRP design have been shown to produce Task 2 to Task 1 priming effects (e.g., Logan & Schulkind, 2000) that look extremely similar to the Task 2 to Task 1 response priming effects we claim to observe here. Watter and Logan (2006) and Thomson et al., (2010) deliberately employed methods to explicitly distinguish semantic category backward compatibility effects from response-related backward compatibility effects and demonstrated that both were present when using semantic categorization tasks where stimuli from both tasks were semantically meaningful and interpretable under both Task 1 and Task 2 categorization rules (e.g., magnitude and parity tasks on digits, or animacy and size judgments on words). As compared with these previous studies, we suggest that our present experiments employed tasks whose semantic categories were relatively weak and unpracticed, with respect to indicating alternative responses. Our tasks also had minimal semantic overlap (stimuli for one task were not semantically meaningful to the other task), suggesting that our observed Task 2 to Task 1 priming effects of S2a-R1 compatibility (and their interaction with R1-R2 compatibility) were likely due to response information arising from S2a. A purely semantic priming account of our observed S2a-R2 effects would have to assume that S2a-related response information was present during overt Task 1 performance (as measured by effects on Task 1) but was unable to directly influence later overt Task 2 response selection.

From a locus-of-slack perspective, a prebottleneck semantic S2a priming effect in Task 2 would be predicted to be underadditive with SOA. While we observe an obvious underadditive relationship across SOAs for S2a-R2 compatibility in our Task 2 data, we suggest that these conditions likely include additional priming effects of attended processing of S2a (with related single-task-like semantic and response process facilitation) at medium and long SOAs, where S2a is still onscreen when Task 1 response selection is complete (a nonnegligible proportion of trials at the 300-ms SOA and, most of the time, for the 900-ms SOA). At short SOAs, where we can more critically examine the unattended influence of S2a, we should predict either observing underadditivity if the prebottleneck Task 2 semantic categorization process still extends beyond the completion of Task 1 response selection to some degree (or still does so on some smaller proportion of trials) or no difference between S2a-R2 conditions if Task 2 semantic activation is maximal (in serial model terms, if the stage is complete) prior to the completion of Task 1 response selection.

In contrast to these predictions of a prebottleneck locus for our S2a-R2 effect, our adjusted RT2 data (controlling for any indirect influence of early cross talk effects on RT1 propagated onto RT2 via locus of slack effects, as discussed above and by Schubert et al., 2008) show a substantial and consistent size of S2a-R2 compatibility effect at 0- and 100-ms SOAs for R1-R2 compatible trials and consistently no S2a-R2 compatibility effect on R1-R2 incompatible trials for these early SOAs. The presence and consistent size of our critical S2a-R2 compatibility effect on R1-R2 compatible trials is inconsistent with a prebottleneck Task 2 semantic locus of this effect. Further, the RSB model (Pashler, 1994; Pashler & Johnston, 1998) predicts that a potential S2a prebottleneck semantic priming effect should not interact with response compatibility effects in a serially discrete response selection stage. Instead, our data show consistent and substantial interactions of S2a-R2 and R1-R2 compatibility relationships, again arguing against a prebottleneck semantic mediation account of our S2a-R2 effects.

A second possible alternative suggested to us is that S2a response information itself may not bypass the bottleneck but, rather, that some representation of the S2a stimulus persists over time and its corresponding response information is later activated during attended Task 2 response selection. According to this alternative, the S2a-R2 compatibility effect observed in these experiments would not be in conflict with the traditional RSB theory because the generation of response information from a persisting S2a representation occurs after the bottleneck, rather than in parallel with Task 1 response selection. We suggest several arguments against this interpretation. If S2a produced only a perceptual or conceptual representation prior to the bottleneck, we might expect the strength of this representation to be relatively diminished when it is eventually used to derive response information during Task 2 response selection, in comparison with that of an S2a stimulus on the screen (which would occur well before overt Task 2 response selection at shorter SOAs). The benefit of computing response activation from S2a immediately is that that response activation can be generated and then persist as it is; in contrast, a persisting conceptual identity representation needs to subsequently drive the computation or selection of another processing stage, in the face of direct perceptual and attentional competition from another stimulus (S2b). Of course, such a possibility could be considered as a reason as to why S2a-R2 influences are relatively small.

Importantly, electrophysiological studies measuring lateralized readiness potentials have demonstrated that response activation for Task 2 does, in fact, begin before the completion of Task 1 response selection (e.g. Lien, Ruthruff, Hsieh, & Yu, 2007; Logan, Miller & Strayer, 2011). While in our present case, these data most directly predict the early generation of S2b response information, we see no reason why these effects should not be generated by S2a in the exact same way. While we cannot conclusively discount the various alternative accounts described above, we suggest that a set of converging evidence from this and other studies is supportive of the notion of early response information generation in Task 2 and that our present data suggest that this information can directly influence overt Task 2 performance with appropriate response conditions.

Conclusions

In summary, while a number of recent studies have shown evidence for parallel activation of Task 2 response information while engaged with overt Task 1 response selection, these data may not violate the core principles of the RSB model (Pashler 1994; Pashler & Johnston, 1998). If response information present following Task 1 response selection is suppressed, as some models suggest may be necessary to resolve interference and binding issues in dual-task performance (e.g., Logan & Gordon, 2001), then attended Task 2 response selection would proceed without any influence of prior automatically activated Task 2 response information computed in parallel with Task 1 response selection. In this situation, Task 2 response selection could be said to be strictly informationally discrete from Task 1 response selection, preserving the essential nature of the RSB model. We present evidence that early Task 2 response information generated in parallel with overt Task 1 response selection does, in fact, persist throughout a trial and across the attentional switch from overt Task 1 to overt Task 2 performance and that this early parallel-generated Task 2 response information influences overt Task 2 responding. In contrast to Schubert et al. (2008), who suggested that early Task 2 response activation influences RT2 only indirectly via propagation of RT1 prebottleneck and bottleneck cross talk effects onto RT2, our data suggest that early Task 2 response information can directly influence RT2, independently of these indirectly mediated effects, in both univalent and bivalent situations when Task 1 and Task 2 responses are compatible. This persistence of early parallel-generated Task 2 response information across the RSB suggests that traditional bottleneck models need modification and suggests some constraints on potential models of human central information processing.

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CHAPTER 5

General Discussion

The PRP paradigm has been used extensively to study dual-task performance. Studies using this paradigm consistently show a cost to Task 2 performance at short SOAs, and this general finding has most commonly been taken as evidence for a strict bottleneck in the process of response selection (Pashler 1984; 1994; Pashler & Johnston 1998). However, investigations of crosstalk in dual-task performance have begun to challenge the idea that response selection for two tasks must proceed serially. These studies have shown that Task 2 response information is generated early enough to influence Task 1 performance. This response compatibility effect seen on RT1 is referred to as the backward compatibility effect, or BCE (e.g. Ellenbogen & Meiran, 2008; Hommel, 1998a; Hommel & Eglau, 2002; Watter & Logan, 2006).

The BCE may have important implications for interpreting mechanisms of dual-task performance, and specifically for determining the extent to which the response selection stages for two tasks may proceed in parallel. The purpose of this thesis was to examine the BCE in detail: to investigate how response information for two tasks is computed in parallel, to determine what stage of processing in Task 1 is influenced by Task 2 response information, and finally to assess whether this Task 2 response information generated in parallel with Task 1 processing actually contributes to explicit Task 2 performance. Each empirical chapter contained its own thorough discussion of the results and relevant theoretical considerations. Therefore, to avoid unnecessary redundancy in this chapter, I will briefly review only the most important findings from each of these investigations, and then highlight a few of the main issues for further discussion.

In Chapter 2, I conducted two studies to investigate how Task 2 response information is computed in parallel with Task 1 performance. The first experiment ruled out the possibility that the BCE is simply the product of S-R relationships learned in Task 1 by providing evidence for a BCE when the Task 1 and Task 2 stimulus sets did not overlap. In this case Task 2 response information could only be generated from stimuli in Task 2, in accordance with the task set mapping rules for that task. The second experiment examined whether Task 2 response information may be generated exclusively from semantic category information for Task 2, in the absence of previously experienced S-R pairs. I observed a BCE in Task 1 even when the Task 2 stimulus was unique on every trial. This finding shows that semantic category information was sufficiently activated from a novel S2, and that this category information was automatically translated, whether episodically or rule-based, to response information in parallel with Task 1 performance. Interestingly, a follow up analysis indicated that there were no significant differences between the two experiments, suggesting that automatic response activation producing the BCE may be substantially mediated by semantic category representations, even when automatic S-R translation is also possible.

In this chapter I also provide evidence that the BCE is not caused by response grouping. If participants withhold their response to Task 1 while they compute the response to Task 2, this strategy could produce a BCE that is not at all related to the computation of Task 2 response information in parallel with attended Task 1 performance. If the BCE is a product of response grouping, the largest effect should be observed on trials with the shortest IRI, where RT1 would be especially long. However I show that the both the BCE and RT1 are relatively consistent across IRI quintiles, and there was generally little evidence of response grouping in these experiments. Therefore the BCE does in fact appear to represent parallel activation of response information in concurrent tasks.

In Chapter 3 I examined which stage of processing in Task 1 is influenced by response information generated for Task 2. In Chapter 1 it was presumed that this response information was generated automatically and in parallel with attended Task 1 response selection, but a plausible alternative is that the post-bottleneck motor stage in Task 1 was influenced by crosstalk arising from attended response selection processing in Task 2. This alternative is fully consistent with the traditional RSB model, which presumes that the two response selection stages operate sequentially. I conducted a training experiment in which participants completed a standard PRP task for six sessions, followed by a test session in which the stimulus set for one of the two tasks was increased. PRP practice shortens the response selection stage of processing which reduces dual-task interference (Ruthruff et al., 2001; 2006; Strobach et al., 2013; Van Selst et al., 1999). I show that the BCE is also reduced with practice, and conclude that it therefore reflects priming of the response selection stage in Task 1, rather than the later motor stage which does not change appreciably with practice. This conclusion is supported by the finding that the BCE is strongly correlated with RT1, and both decrease reliably with practice as the central stage in Task 1 is shortened. More support for the claim that the

BCE acts on the central response selection stage in Task 1 is demonstrated in the data from the final test day: lengthening the Task 1 response selection stage by increasing the Task 1 stimulus set leads to a re-emergence of the BCE, as well as an increase in RT1. By contrast, increasing the duration of Task 2 response selection by increasing the stimulus set for this task has no effect on the BCE or on RT1. I conclude that the BCE does in fact represent parallel activation of response information for two tasks that acts on the central bottleneck stage in Task 1 performance.

Finally, and perhaps most importantly, in Chapter 4 I examine the ultimate outcome of the Task 2 response information that is generated in parallel with Task 1 performance and produces the BCE. If this information does not persist across the bottleneck and the attentional shift between tasks, the bottleneck remains functionally and informationally intact. Using an adapted PRP paradigm with a brief prime stimulus in Task 2, I was able to show that early Task 2 response information generated in parallel with attended Task 1 processing does in fact contribute to Task 2 performance. This was true for both bivalent and univalent-mapped stimuli, and critically even after controlling for indirect effects on Task 2 propagated from Task 1. However, this bypass effect was only present for response compatible trials. When the responses were incompatible across tasks (represented as different fingers on the same hand for bivalent stimuli, or a different finger identity on the opposite hand for univalent stimuli), early Task 2 response information did not influence eventual Task 2 performance. These findings suggest that the resetting of response information between tasks may not be all or none as ECTVA assumes (Logan & Gordon, 2001), but is instead contingent on response compatibility across tasks. In Chapter 4 I discuss a number of potential mechanisms underlying this variably-sensitive response suppression, as well as a number of alternative explanations for the observed results. The important and novel contribution from this work is the evidence that the bottleneck is leaky, at least in certain situations, and that in such contexts the BCE does in fact represent a violation of the discreteness assumption of the RSB model.

Recurring Observations

Throughout these studies there were a number of consistent patterns of results that merit further discussion. In both Chapter 2 and Chapter 4, the data revealed mixed compatibility effects in RT1, such that all-compatible or all-incompatible trials were performed faster in Task 1 than trials of mixed or partial compatibility. In Chapter 2 this effect was observed as an interaction between semantic and response compatibility in RT1, while in Chapter 4 the mixed compatibility effect was observed as an interaction between the compatibility of the responses associated with the two different Task 2 stimuli with that of the Task 1 stimulus (S2a-R1 x R1-R2). I noted that this latter interaction could be simplified by redefining it as a main effect of S2a-R2 compatibility on RT1 (Schubert et al., 2008), but the mixed compatibility effect in both chapters could also be caused by partial repetition effects as discussed by Hommel (Hommel, 1998b, 2004, 2007; Hommel & Colzato, 2004). Hommel proposed that stimulus features and associated actions are bound together in event files, and that subsequent encounters with a bound feature of a recently active event file retrieves the file in whole or in part. Partial repetition costs arise when only some of the features of an event are repeated, as feature integration is slowed for feature overlapping, but non-identical events. In the experiments in Chapter 2, a partial repetition effect in Task 1 performance may occur when S2 retrieves the same semantic category feature as S1 under the Task 1 mapping rules, but a different response under its own (Task 2) rules, or vice versa. In Chapter 4 the partial match occurs in Task 1 when S2a retrieves a response that is compatible with S1 but S2b does not, or vice versa. If these patterns of data do, in fact, represent partial repetition effects akin to Hommel's event file model, they suggest that not only do these effects occur across trials in a single task experiment, but they may also be observed when the partial match is driven by different features of a single stimulus or multiple not-yet-attended stimuli, which may interfere with the integration of features across perception and action for the primary task.

The interaction between semantic and response information for Task 1 observed in Chapter 2 also provides evidence that the BCE occurs at the level of central and abstract response code representation rather than the later response execution stage. Although this claim was explicitly investigated in Chapter 3, it was also implicitly supported in Chapters 2 and 4. It is unlikely that the semantic representation of the stimulus category is relevant to motor execution. Rather, the interaction between response compatibility (the BCE) and semantic compatibility in Chapter 2 implicates a more central locus for the effect. In addition, in Chapter 4 a BCE was observed across both univalent and bivalent response mapping conditions, as well as under a different definition of response compatibility than in an earlier related study. Specifically, in Schubert et al. (2008), response compatibility across hands was defined spatially (e.g.

leftmost response key for Task 1 using the left hand was defined as compatible with the leftmost response key for Task 2 using the right hand), while the current study defined response compatible trials as those using the same finger identity across hands (e.g. index finger response using left hand for Task 1 was compatible with an index finger response using the right hand for Task 2). This discrepancy is likely based on differences in the type of stimuli (spatial or not) and task rules applied in the two studies. Taken together, these findings in Chapter 4 suggest that the BCE is based on compatibility between abstract representations of response codes, rather than actual motor commands. This interpretation is consistent with the evidence in Chapter 3 demonstrating that the BCE acts on the central response selection stage of processing.

Another consistent finding across these studies is an SOA effect on Task 1 performance: RT1 at short SOAs was almost always longer than RT1 at the longest SOA. This was true in both experiments in Chapters 2 and 4, and although not assessed specifically, was also true for at least the early training sessions in Chapter 3. Importantly, there is little reason to suppose that the Task 1 slowing at short SOAs is caused by participants withholding their response to that task while they attend to Task 2. In Chapter 4, participants had very few short IRIs, meaning that they executed their response to Task 1 well before that of Task 2. In Chapter 2 I showed that RT1 does not change substantially across IRI quintiles, and this also provides evidence against response grouping.

If participants are not grouping their responses at short SOAs, what causes the increase in RT1? One possibility is that the simultaneous or near-simultaneous onset of stimuli for both tasks surprises or distracts participants briefly, disrupting processing and causing a slight increase in RT at these SOAs. Another possibility is that this increase in RT is a marker of parallel processing. If parallel processing leads to an increase in RT, it might suggest that some capacity for Task 1 processing is being used to process the Task 2 stimulus. Such a capacity sharing account differs mechanistically from the automatic S-R or C-R translation processes discussed in this thesis, which do not explicitly depend on the division of resources across tasks. It is therefore important to consider whether the data presented in this thesis might be accounted for according to other models of dual-task performance.

Implications of the present studies for models of dual-task performance

It seems clear that the data presented in the empirical chapters are not compatible with the traditional RSB model of dual-task performance, at least as strictly defined by Pashler & Johnston (1998) where the bottleneck occurs in the process of mapping stimuli to responses. Chapter 2 shows that response information can be activated from the abstract category representation of a Task 2 stimulus in parallel with attended Task 1 performance, causing a BCE in RT1. Chapter 3 provides further evidence that the BCE is an effect of crosstalk on the response selection stage of Task 1 performance rather than the post-bottleneck motor stage. The strongest evidence against the traditional RSB model is provided in Chapter 4, where I demonstrate that the response activation generated for Task 2 in parallel with Task 1 persists to contribute to explicit Task 2 performance. This indicates that the central stages of processing for these two tasks are not discrete even in a functional sense, thereby violating the fundamental assumption of the RSB model. It appears that the process of activating response information does not proceed discretely for two separate tasks.

A common alternative to the RSB model is a graded capacity or resource sharing model (e.g. Navon & Miller, 2002; Tombu & Jolicoeur, 2003), which was briefly mentioned in the introduction. This type of model has been shown to account for many of the same findings as bottleneck models, such as the SOA effect on RT2, and the slope of RT2 approaching -1 at short SOAs. Graded capacity sharing resource models can also explain the pattern of underadditivity of manipulations on pre-central Task 2 processes with SOA. Additionally, capacity or resource sharing models predict the increase in RT1 with decreasing SOA, observed in these studies and elsewhere (Pashler & Johnston, 1989; Ruthruff, Pashler & Hazeltine, 2003; Sigman & Dehaene, 2006; Tombu & Jolicoeur, 2002). Importantly, they are also well equipped to account for crosstalk effects between tasks, such as the BCE, as they predict that the rules for two tasks are held concurrently in working memory and executed simultaneously, although often with disproportional resources allocated to Task 1. However, the notion of divisible attentional resources has been contested in the literature (e.g. Bonnel & Prinzmetal, 1998; Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997; Lee, Koch, & Braun, 1999), and a number of the current results are not expressly predicted by a capacity sharing account. For example, the PRP effect, the BCE, and RT1 all decrease with practice (Chapter 3). A capacity sharing model may also account for the reduction in the PRP effect with practice by positing that participants become more proficient at sharing capacity more evenly across tasks. As compared with the start of training, fewer of the limited resources are allocated to Task 1, and more become allocated to Task 2. This would slow processing in Task 1 (Navon & Miller, 2002; Tombu & Jolicoeur, 2003), which would at least partially offset the benefit of practice on RT1. The finding in Chapter 3 and elsewhere that the decline in the PRP effect closely tracks the decline in RT1 (Ruthruff et al., 2001, 2006; Van Selst, et al., 1999), while not incompatible with a capacity sharing account, is directly predicted by a bottleneck model with central capacity shortening. More resources allocated to the processing of Task 2 over practice might also lead to more strongly represented response information for Task 2 generated in parallel with Task 1 processing, potentially allowing for a larger BCE with practice (though again offset by decreases to RT1 with practice). I found that the BCE decreased with practice, again proportional with the decrease in RT1, which fits more cleanly in a bottleneck than a capacity sharing model. Finally, although a capacity sharing model could predict the crosstalk effects observed in Task 1 in the present studies, it cannot easily account for the finding of an S2a effect on Task 2 performance only when the responses are compatible across tasks (Chapter 4).

Meyer and Kieras' (1997a; 1997b) EPIC architecture can also account for the BCE in Task 1 performance. EPIC places special emphasis on task strategies and executive processes, and rather than assuming capacity limitations exist in central processing, it places constraints on the peripheral perceptual and motor processors. EPIC employs a strategic response deferment (SRD) model, which presumes that the response selection stage of two tasks can occur simultaneously, but at short SOAs Task 2 operates in 'deferred mode', where its responses are temporarily stored in working memory rather than being sent directly to the motor processors. Once Task 1 is completed, Task 2 must be unlocked (i.e., transferred from deferred to immediate mode by the executive) before the response information is sent to the motor processor. This strategic deferment and unlocking ensures that the tasks are performed in the correct order and that there is no confusion at the level of motor output. In this situation, EPIC behaves essentially as a bottleneck model with slack occurring after Task 2 response selection and prior to Task 2 motor programming on short SOA trials (c.f. Path 1, Meyer & Kieras 1997a). One implication of this model is that priming effects on response selection for Task 2 at short SOAs, such as the S2a-R2 compatibility effect observed in Chapter 4, should be absorbed into the slack while Task 2 waits for Task 1 execution and the subsequent Task 2 unlocking process to complete (Figure 1). The S2a-R2 compatibility effect should only influence RT2 if the final response execution stage for Task 1 and Task 2 unlocking have completed before response selection for Task 2 is finished. However, this is very unlikely at short SOAs. In order for this to be the case, it would also mean that response execution for Task 2 has not been deferred at all at short SOAs, thus arguing against one of the central assumptions of the model.

It is worth noting that this logic only applies on short SOA trials. At intermediate SOAs, the slack in Task 2 processing occurs earlier, either mid-selection or even pre-selection, when Task 1 is complete and Task 2 processing is put on hold while excecutive processes tranfer it from deferred to immediate mode. With sufficiently long SOAs this

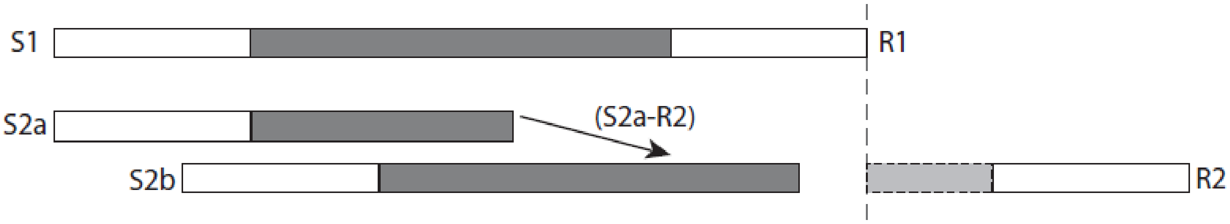

Figure 1. Sequence of processing events implied by strategic response deferment at a short stimulus onset asynchrony (SOA). Dark gray shading indicates the response selection stages, which may proceed in parallel according to the EPIC architecture; light gray shading indicates the Task 2 unlocking process. When the SOA is very short Task 2 reaction time (RT) contains postselection slack. The S2a-R2 priming effect may be absorbed in this slack and therefore not observed in Task 2 RTs.

process occurs before the onset of S2, and there is no delay in Task 2 processing. In all of these instances, the S2a-R2 compatibility effect would not be absorbed into the slack and therefore may be observed in RT2. According to this interpretation, then, the only data from the present thesis that are not easily accounted for by EPIC and its SRD model are the S2a-R2 compatibility effects observed on 0 and 100 ms SOA trials, and that these are observed exclusively on response compatible trials.

One potential explanation for the S2a-R2 compatibility effect observed at short SOAs is that instead of deferring response execution for Task 2, EPIC may selectively operate in a more daring mode to promote entirely parallel performance for both tasks. However, this more daring task scheduling approach should result in very fast but likely more errorful performance, and does not fit with the slow RT2 data I observed in each of the present studies.

Logan and Gordon’s (2001) ECTVA does not involve any structural serial limitations in central processing, and it attributes dual-task interference to control processes responsible for task scheduling. As discussed in Chapter 4, the model can be configured to run in parallel, but predicts that individuals respond serially in dual task situations because TVA (Bundesen 1990) is faster and more accurate when performed in series than in parallel, since serial processing naturally avoids response perseveration and the binding problem. ECTVA can also account for findings of crosstalk and concurrence costs in Task 1 (Logan & Gordon, 2001). By default, ECTVA resets its random walk response counters between tasks to 10% of their level upon completion of Task 1. This incomplete flushing of response information between tasks fits well with the S2a-R2 bypass effect observed in Chapter 4, where Task 2 response activation computed in parallel with attended Task 1 performance contributed at least somewhat to eventual Task 2 performance. However, the data from that study also indicated that this bypass effect is contingent on response compatibility between tasks, and this finding cannot be explained by the current version of ECTVA. The model would need to be modified to account for the selective gating of response information between tasks depending on the level of overt response compatibility, perhaps via either conflict monitoring or episodic control. Otherwise, our findings are generally quite consistent with the predictions made by ECTVA in dual-task situations.

The present findings are also consistent with Hommel's (1998a) suggestion of an automatic, parallel response activation stage that precedes a controlled, serial response selection stage. Both Hommel's model and ECTVA predict that components of processing can proceed in parallel while others are serial. The main difference is that ECTVA predicts that processing *could* run entirely in parallel, but by including a serial component it incorporates a mechanism for avoiding cross-task interference and successfully binding stimulus information with the appropriate response. Hommel's model seems to suggest that the final serial selection stage is obligatory. In Chapter 4 I discuss alternative possibilities for how a parallel response activation stage may be incorporated into a bottleneck model with serial response selection, and show that it is difficult to interpret response activation as a separate stage in a discrete stage model. Instead, this stage does not appear constrained by serial locus of slack logic. However, if response activation for Task 2 can proceed in parallel with serial response selection in Task 1, this accounts well for the S2a-R2 priming observed in Chapter 4. Once again the model would need to incorporate a mechanism for selectively gating the contribution of the parallel response activation stage contingent on overall response compatibility between tasks.

One interesting question raised by this model of dual-task performance is what cognitive processes are performed during the serial response selection stage. If the work of accruing response activation is started and, perhaps, completed in the response activation stage, why does the subsequent response selection stage require controlled and serial performance? In a number of single task models that incorporate cascaded processing, response selection occurs instantaneously the moment response activation processes reach a given threshold; there is no additional process specifically devoted to selection (e.g. Coles et al., 1985; McClelland, 1979). It seems plausible that this specific selection stage is predominantly required in dual-task situations, which have now been shown to involve parallel computation of responses. In these situations, the serial selection stage provides a functional solution to the binding problem that arises when multiple stimuli activate responses concurrently. This binding likely requires selective attention to integrate the appropriate stimulus and response features for each task in series, producing the typical RT2 costs associated with dual-task performance.

Conclusion

The studies in this thesis were designed to investigate the nature of the BCE and its implications for mechanisms of dual-task performance. Each of the empirical chapters assessed one important aspect of the response information computed for Task 2 that produces the BCE observed in Task 1: the potential mechanisms underlying it, its locus in the processing stream, and its ultimate influence on Task 2 performance. The results of these investigations have demonstrated that the BCE reflects the activation of response information for Task 2 in parallel with attended response selection in Task 1, via automatic S-R or C-R translation. Critically, this Task 2 response information is able to persist across the attentional shift between tasks to contribute to eventual Task 2 performance.

This work represents an important step toward understanding the mechanisms of dual-task processing. However, much work still needs to be done to further delineate the component building blocks of cognitive processing involved. As suggested above, future work should further investigate what exactly is involved in the serial process of response selection, as well as the degree to which a serial component of processing in dual-task performance is strategic or obligatory. Further investigations into the cognitive mechanisms supporting selective resetting of response information between tasks in a PRP paradigm will also be important for updating current models of dual-task performance, and potentially elucidating which of these can best accommodate the accumulating dual-task data demonstrating backward, response-level crosstalk effects between tasks. The work presented in this thesis contributes important and converging evidence that response activation for two tasks may proceed substantially in parallel, but also highlights the important serial constraint that is still observed in response selection processing. Contemporary models of dual-task performance must therefore consider mechanistically distinct processes of response activation and response selection, with selective attentional limitations placed only on the selection stage.

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