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What causes dual-task costs?

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WHAT CAUSES DUAL-TASK COSTS?

by

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CERTIFICATE OF APPROVAL

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PH.D. THESIS

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CHAPTER I

INTRODUCTION AND BACKGROUND

Humans are constantly attempting to multi-task in an effort to work more efficiently. This kind of behavior is encouraged by developments in technology that allow us to always be "plugged in", online, and constantly switching from one task to the other. It is very common to see people composing an email on their phone while listening to someone speak, changing songs on an iPod™ while driving, or having multiple windows open on their computers. Although many devices are being marketed as "time-savers" and bosses push multi-tasking to increase workplace efficiency, evidence from laboratory experiments shows that almost every time people attempt to do more than one thing at a time, performance becomes worse on one or both tasks.

What are dual-task costs?

When humans attempt to do more than one thing at the same time, performance usually suffers. Sometimes difficulties arise because of peripheral interference; for example, it is impossible to execute two distinct motor movements with the same effector simultaneously or to make two distinct verbal responses at the same time. However, dual-task costs, or the performance decrements that result from doing two tasks simultaneously, occur even when there is no peripheral interference. These costs are assumed to arise instead from competition for central response selection mechanisms and have been reported in both laboratory (e.g., Kahneman, 1973; Pashler, 1994; Tombu & Jolicœur, 2004) and real-world scenarios (e.g., Strayer, Drews & Johnston, 2003) in situations in which neither input nor output modalities overlapped. Dual-task costs that arise from central interference will be the focus of the work presented here.

Dual-task costs are often observed even when both tasks are relatively simple, and use distinct input and output modalities. In experimental settings, researchers often measure the amount of interference that occurs when two tasks must be performed simultaneously by comparing reaction time (RT) in dual-task situations compared to single-task situations. In one of the seminal dual-task studies, Davis (1956) had participants make two distinct manual responses to visual stimuli that appeared in a predictable order separated by a variable stimulus onset asynchrony (SOA). The results showed that participants' second response was significantly slower on dual-task trials compared to the average mean RT for a single button press. Even if the stimuli were presented sequentially, giving the participants ample time to perceptually encode them, there were large costs to performance so long as the time between the two tasks was less than 250 ms (the average amount of time required to complete one of the tasks in isolation). Subsequent dual-task studies have shown that even tasks in which the responses were not both manual (e.g. one was manual and one was verbal) reveal a similar pattern of interference (e.g., Pashler & Johnston, 1989).

Overview

It is somewhat surprising that asking participants to perform two simple tasks without peripheral interference results in such large performance decrements, yet this is almost always the case. Perhaps the most common conclusion, given the seemingly ubiquitous presence of interference during multi-tasking, is that dual-task costs arise because structural limitations in the response selection mechanisms prevent two responses from being selected concurrently (see e.g., Pashler, 1994). However, recent dual-task studies suggest that task demands created by the instructions, timing, and experimental paradigms most frequently used to study dual-task interference may be inflating the magnitude of the observed costs. In fact, a few studies have shown evidence of very efficient dual-task performance, in which almost no difference in RT between dual- and single-task blocks was observed (see e.g., Greenwald & Shulman, 1973). These studies used stimulus-response (S-R) pairs with a unique and highly compatible relationship. They also manipulated a number of the aforementioned factors, like timing, instructions, block types, and the order of events that, may have contributed to the drastic difference in the magnitude of the dual-task costs. These factors will collectively be referred to as the task structure.

Task structure can influence dual-task performance in many ways. In the following sections, I will discuss the specific aspects of the task structure that have been shown to influence the magnitude of dual-task costs. One of these factors has to do with which single-task trials are used for comparison. When people are required to do two things as compared to one, not only must the second response be initiated and executed, but the S-R mappings for the second task must be maintained in working memory. For example, when a person is driving and talking on a cell phone via a hands-free headset, dual-task costs might emerge from the strain of having to keep the rules associated with both tasks active; the individual has to keep the content of the conversation in mind as well as continue to monitor his or her position on the road, speed, and direction for getting to the final destination. The maintenance of these rules leads to an increase in cognitive load that is not present during trials in which participants are only making one response to one task on every trial, known as mixing costs. As such, adding a second task changes more than one thing between single- and dual-task trials. Importantly, different types of single task trials provide distinct measures of the possible sources of dual-task interference. Moreover, research has shown that when the stimuli for the two tasks are presented with a variable stimulus onset asynchrony (SOA), participants adopt a serial response strategy that causes significant dual-task costs in RT, even when it may be possible to perform both tasks simultaneously (see e.g., Schumacher et al., 2001; Halvorson et al., 2012).

In light of the fact that these factors of the task structure have been shown to influence dual-task performance so drastically, it difficult to determine if dual-task costs are indeed caused by structural limitations within the brain, or performance limitations caused by the task structure. To date, very few studies have shown evidence of perfect time-sharing, or no difference in RT between dual- and single task trials. One of the only reported instances of perfect time-sharing with neurologically intact participants used a type of task, known as Ideomotor (IM)-compatible tasks, in which the relationship between the stimuli and responses was highly compatible (Greenwald & Shulman, 1973). However, these findings have since been challenged, and subsequent attempts to replicate the finding of perfect time-sharing have resulted in significant dual-task costs (e.g., Lien, et al., 2002). Recently, Halvorson et al. (2012) investigated some of the possible factors that could account for these differences, and showed that when the appropriate measure of single-task performance was used, IM-compatible tasks do indeed allow for dual-task performance that is as efficient as single task. However, the results from Halvorson et al. (2012) showed that both tasks must meet the criteria for IM-compatibility in order for dual-task costs to be eliminated; dual-task costs varied dramatically depending on the two tasks. In some cases, tasks that did not result in dual-task interference when paired with one type of task showed significant performance decrements when paired with another. Thus, the magnitude of the dual-task costs depends critically on the task pairing.

As will be discussed in the following sections, the finding of perfect time-sharing only when the task pairing consisted of two IM-compatible tasks is in conflict with the original explanation for why IM-compatible tasks avoid dual-task costs. Thus, the aim of this work is to systematically manipulate factors associated with the task pairings used in Halvorson et al. (2012) to investigate the source or sources of dual-task interference. Because many theories of response selection make strong claims about the structural limitations associated with dual-task performance, a great deal of effort has been put into demonstrating that RTs in dual- and single-task blocks can never be identical. However, by focusing on obtaining a zero millisecond difference in RT, dual-task studies have overlooked dramatic changes in RT (e.g., a dual-task cost of 100 ms in some cases, and 10 or 20 ms in others) and the factors giving rise to these changes. In the studies presented here, the focus will not be on obtaining a 0 ms difference between single and dual-task conditions; rather, the goal is to identify factors of the task pairing that lead to dramatic changes in the magnitude of the dual-task costs.

How should dual-task costs be measured?

While it is indisputable that dual-task costs should be estimated by comparing performance when only one response is required to performance when two responses are required, there are distinct, and potentially separable, types of costs that are associated with doing two things at the same time. For instance, when a person is driving and talking on a cell phone via a hands-free headset, dual-task costs might emerge from the strain of having to keep the rules associated with both tasks active. For example, the individual has to keep the content of the conversation in mind as well as continue to monitor his or her position on the road, speed, and directions necessary for getting to the final destination. Alternatively, dual-task costs could be a product of actually programming the movements required for both tasks; even though it's possible to move our mouth and our hands simultaneously, executing these responses in parallel could be giving rise to the performance decrement. These different sources of interference make it difficult to isolate dual-task costs to a single comparison. The various types of single- and dual-task trials used for comparison will be discussed in detail in the sections to follow.

Moreover, the timing of the sequence of events and changes to the task structure (like instructing participants to prioritize one task over the other) has been shown to dramatically increase dual-task costs in some cases. There is a second timing issue that concerns the duration of the response selection stage. In cases where the central stage is presumed to be very short for each task, measures of response time may not reveal dual-task costs; it could be that response selection is happening concurrently for both tasks but it could also be that the latency for the response selection stage is so short that each task can be processed serially without slowing responses. Further, research has shown that dual-task costs vary across individual participants and may reflect preferences or strategic choices rather than structural limitations associated with response selection. Some researchers have turned to measures besides RT to examine how selecting the response for one task might influence response selection for the other. Each of these issues will be taken up in the following sections.

Measures of single task performance

Although researchers unanimously agree that measures of dual-task costs should reflect the difference between making two responses and making only one response, changes to the task structure can affect measurements of both single- and dual-task costs. Single-task response times can be measured by using blocks in which only one task is performed throughout (homogenous blocks) or from single task trials that are part of mixed blocks, which include both single and dual-task trials. Response times on dual-task trials could be slowed compared to single-task trials from homogenous blocks simply because adding a second task also increases the number of S-R pairs that must be maintained in working memory. According to the Hick-Hyman law, the added load of an increase in the set size will slow performance even when only one response is required (Hick, 1952; Hyman, 1953). Because dual-task blocks necessarily contain more S-R pairs that pure, single-task blocks, performance impairments unassociated with actually choosing and executing two responses may result in overestimating the dual-task costs. Thus mixing costs, or the decrement in RTs associated with increased cognitive load, as well as switch costs, which arise from adjustments in processing that occur when alternating between one stimulus set and the other, might be slowing dual-task performance (see Los, 1996).

To eliminate these costs from the measure of dual-task costs, some researchers (see e.g., Greenwald, 2003) include mixed-task blocks, which contained single-task trials from both task sets presented in a random order but never simultaneously, to serve as a baseline. Response times were significantly longer in the mixed blocks than in the simultaneous blocks, suggesting that in some cases, measures of dual-task costs could have included costs arising from switching between stimulus sets. Greenwald (2003) also reported longer RTs in the mixed blocks than in the pure, single-task blocks, even though participants were only making one response at a time in both conditions. This suggests that some of the costs typically measured in dual-task paradigms are not solely associated with actually making two responses.

In one experiment, Tombu and Jolicoeur (2004) used three types of blocks to evaluate dual-task performance: pure single-task blocks consisting only of single-task trials from one task, OR blocks consisting of single-task trials from both tasks, and AND blocks consisting of only dual-task trials. When the authors compared the AND blocks with OR blocks, there was no significant difference between single and dual-task RTs. However, RTs from the AND blocks were significantly slower than RTs in the pure single-task blocks. These results underscore the idea that dual-task costs can be computed in multiple ways, and different methods can lead to divergent conclusions.

On the one hand, several studies report increases in RT from single-task to mixed blocks (e.g., Greenwald, 2003; Schumacher et al., 2001). It is possible that this increase in RT reflects a significant change in the amount of preparation participants are capable of on OR trials as compared to single-task and AND trials. In the single-task and the AND blocks, participants can completely prepare for the task or tasks that they will perform in the upcoming trial, which may suggest that heterogeneous OR blocks are not the best baseline for dual-task comparisons. On the other hand, the requirements to attend to multiple sources of stimuli, maintain two sets of mappings in working memory, and adequately prepare multiple types of responses seem distinct from interference related to concurrent task operations. For example, with two-choice tasks, there are two possible responses on single-task blocks, four possible responses on OR blocks and 4 possible responses on AND blocks. Increasing the number of alternatives increases mean RT under single-task conditions (Hick, 1952; Hyman, 1953), and it is reasonable to want to dissociate this effect from a dual-task cost, so comparisons between AND and OR blocks would seem most appropriate.

Because it is not clear which type of trial provides the most appropriate baseline from which to evaluate dual-task costs (or even whether this question can be definitively answered), in all the experiments reported here (see also Halvorson, Ebner & Hazeltine, 2012) I opted to compare two measures of single-task performance: pure single-task blocks (e.g., Schumacher et al., 2001), and mixed single-task blocks, henceforth called OR blocks, (e.g., Greenwald, 2003; Tombu & Jolicouer, 2004), with one measure of dual-task performance. I eliminated the instructional manipulation often included in dual-task experiments that requires participants to prioritize one task over the other, and presented both stimuli simultaneously on all trials in the dual-task blocks. In the dual-task blocks, henceforth called AND blocks, there was a 0 ms SOA on all the trials. I used the difference between performance in the OR blocks and single-task blocks to look at the effect of mixing costs (i.e., the strain of keeping both tasks active) when the number of responses was kept constant. I compared performance in the AND blocks, when two responses were required, to performance in the OR blocks to obtain a measure of the difference between single- and dual-task performance when the strain of maintaining two tasks was kept constant.

Timing

There are two main issues of timing associated with measuring dual-task performance. The first is that traditional dual-task paradigms that include a variable SOA may result in participants adopting a serial strategy which causes the appearance of dual-task costs, even if it is possible for participants to do both tasks simultaneously. This issue was taken up in Halvorson et al. (2012) and Greenwald (2003), which showed that the exact same tasks that produced costs when a variable SOA was used can be performed simultaneously when the stimuli for the two tasks are presented at the same time (see also Schumacher et al, 2001). In general, presenting the stimuli simultaneously appears to be more conducive to minimizing dual-task costs.

However, presenting the stimuli at the same time on every trial highlights a second timing issue in dual-task performance; simultaneous presentation requires that the encoding stage takes place simultaneously for both tasks. Some theories of response selection that allow for encoding multiple stimuli in parallel but require that the actual response selection takes place serially. Researchers argue that if it simply takes longer to encode one stimulus than the other, two tasks that have a very short central stage could make use of the central mechanisms serially which would result in a negligible delay in RT. This would make the bottleneck stage almost impossible to detect with measures of RT.

In these cases, it may be that responses are being selected for each task independently of response selection for the other task and only the stages that can occur in parallel (i.e. stimulus encoding or response execution) overlap. This issue can be addressed in part by showing that the presence or absence of dual-task does not vary systematically with costs the time it takes to perform each task. Lengthening RTs without changing how difficult it is to encode the stimuli or execute responses typically reflects a longer response selection stage. Halvorson et al. (2012) showed that two four-choice IM-compatible tasks resulted in slower overall RTs (in the VM task) without resulting in dual-task costs.

Individual Differences and Strategy

Dual-task studies show that individuals can vary dramatically in their ability to respond to two tasks at the same time. Practice studies have shown that some participants appear to be more willing to perform two tasks simultaneously (Schumacher et al., 2001). Schumacher and colleagues (2001) conducted a practice study in which participants performed two choice-RT tasks. After five sessions in which the two stimuli were presented simultaneously, dual-task costs were eliminated. Schumacher and colleagues calculated the expected dual-task interference for each participant if costs were accrued in a systematic way. The expected value was calculated based on three assumptions: all task processing and scheduling was the same for the participants; mean dual-task costs were the same for all participants; the only variable present in the dual-task costs was from random, trial-to-trial variability as seen in blocks of single-task trials. These uniform amounts of dual-task costs did not match the observed costs for participants. In fact, most of the participants' costs were significantly higher or lower than this expected cost. The authors suggested that these differences were the result of different strategies adopted by participants. The participants in the study were relatively evenly distributed into groups of low, moderate, and high interference, presumably reflecting the adoption of a strict serial schedule, something like a mix between parallel and serial processing, and a greater willingness to attempt parallel processing (at the expense of making more errors), respectively. However, even when many people show little evidence of costs, there can be outliers who appear to adopt a serial strategy regardless of the tasks (Halvorson, et al., 2012).

Data from the same study (Schumacher et al., 2001) showed that changes to the instructions can cause even participants who were previously performing two tasks without cost (in parallel) to adopt a serial response strategy. In a follow-up experiment with the same participants, the authors modified the task to include a variable SOA and instructions to prioritize one task over the other (Schumacher et al., 2001). With these changes, even the participants who were the most willing to adopt a parallel response strategy and showed the least amount of dual-task interference in RT responded in a manner consistent with serial processing. These findings suggest that the structure of the task and participants' strategies may be inducing a PRP effect, or dual-task cost, even when there is no processing limitation for the two tasks (see also, Hazeltine et al., 2008; Isreal & Cohen, 2010).

Theories of response selection and dual-task predictions

In this section I will review existing theories of response selection and the various predictions they make about dual-task performance and when interference should be observed. First I will discuss bottleneck models, perhaps the most common model used to explain the presence of dual-task costs, followed by a brief review of resource models, crosstalk models, strategic models and models in which responses are selected according to fast-acting procedural rules. All of these models make slightly different claims about the necessary conditions required to observe dual-task costs, but none of them are mutually exclusive. However, it is important to detail each of these accounts because explanations for why costs may not be observed in some situations depends critically on what circumstances a given theory of response selection predicts *would* result in dual-task costs. Ultimately, understanding the factors that give rise to dual-task interference should constrain theories of response selection, even under single task conditions.

Bottleneck Models

According response selection bottleneck (RSB) models, dual-task costs are hypothesized as reflecting the operation of a particular stage of processing that cannot be shared by two concurrent tasks (Welford, 1952; Davis, 1956; Pashler, 1984, 1994). According to such accounts, this stage acts as a processing bottleneck, preventing humans from carrying out two tasks at the same time (e.g., Pashler & Johnston, 1989). It is generally assumed that the bottleneck stage involves operations that can be roughly characterized as response selection – that is, the translation of a categorized stimulus into an abstract representation of the appropriate response (Pashler, 1994). The exact composition of the bottleneck stage is a complex issue as it may include multiple, distinct processes (see, for example, Ruthruff, 1995; Tombu & Jolicœur, 2005; Salvucci & Taatgen, 2008), but essential to the RSB model is the claim that choosing a response based on a stimulus input – that is, performing a choice reaction time task – engages a single channel process that operates on tasks in a serial fashion.

Much of the support for RSB models comes from studies that use the psychological refractory period (PRP) procedure to examine dual-task costs. PRP studies have been used to test the limitations of the underlying cognitive mechanisms that are involved in stimulus-response selection processes, and the decrements in performance that result from doing multiple tasks are generally interpreted as reflecting the operation of at least one stage of processing that cannot be shared by two concurrent tasks (Welford, 1952; Pashler, 1984, 1994; Davis, 1956).

In this procedure, two stimuli are presented in succession with varying stimulus onset asynchronies (SOAs). Typically, whenever two stimuli (S1 and S2) require two distinct responses (R1 and R2), significant performance decrements in response time (RT) are revealed when participants are required to complete both tasks as compared to when they are only asked to do one task. In this paradigm, participants are explicitly instructed to prioritize Task 1 such that responding to Task 2 never interferes with Task 1. This is done to avoid scenarios in which participants delay responding to one task until processing for the other task is also completed; a phenomenon known as response grouping. By keeping RTs to Task 1 consistent, dual-task interference can be measured by the increase in Task 2 RTs. This paradigm produces robust findings of a systematic relationship between Task 2 RT and SOA such that the slope of Task 2 RTs is -1 at short SOAs. This suggests that as the SOA decreased in time, there was a corresponding increase in Task 2 RT which is consistent with the prediction that Task 2 will be delayed until response selection for Task 1 is fully completed (see Welford, 1959). Additionally, early PRP studies showed that the increase in Task 2 RT at the 0 ms SOA was equal to the RT of Task 1 which suggests that Task 2 processing did not begin until Task 1 was finished.

Latent Bottleneck Models

Critically, bottleneck models contend that structural limitations prevent simultaneous response selection from occurring. Thus, dual-task scenarios should always lead to costs in measures of RT because the second task must be postponed until response selection has been completed. However, there have been a few notable instances where the difference in RT between dual-task conditions and single-task conditions has been non-significant for all the participants in the PRP task (Hazeltine et al., 2002). Hazeltine, Teague and Ivry (2002) used a practice paradigm to show that when a brief simultaneous onset was used between stimulus presentations, after a sufficient amount of practice two relatively simple tasks without overlapping input or output modalities could be performed without impairment. In light of these findings, researchers have proposed that after some amount of practice with simple tasks, participants can perform two tasks nearly simultaneously without much evidence of dual-task costs *and* without ruling out the presence of a bottleneck (Ruthruff, Johnston, Van Selst, Whitsell & Remington, 2003). These researchers propose a latent bottleneck model, which claims that in many of the tasks used in instances of perfect time-sharing, the bottleneck has become so short that the delay caused by the first task occupying this stage is no longer visible with the standard range of SOAs.

In order to test the latent bottleneck hypothesis, in follow-up experiments, Hazeltine et al. (2002) manipulated task difficulty, the compatibility of the S-R mappings, and stimulus onset asynchrony (SOA). These manipulations should either lengthen the central response stage or cause it to overlap. If competition for central resources causes dual-task costs, then these manipulations should result in performance decrements even though the S-R pairs remained identical. However, the authors found evidence of perfect time-sharing in these conditions, even though the task structure was altered such that the response selection stages for each task very likely overlapped. These results challenge theories of response selection that require a strict interpretation of the structural bottleneck. Importantly, even though participants could achieve non-significant dual-task costs after moderate amounts of practice, alternative measures (e.g. correlations between RTs for the two tasks) of interference showed that the two tasks were not completed totally independently.

Subsequently, Anderson, Taatgen and Byrne (2005) used a computational model of executive functioning based on production rules known as the Adaptive Character of Thought (ACT-R) to simulate the findings from Hazeltine et al. (2002) with the intention of proving that a model that includes a structural bottleneck can account for the behavioral findings of perfect time-sharing. Anderson and colleagues used ACT-R to show that the model, which allows the central response selection stage to choose the correct response in only 50 ms, can accurately simulate the behavioral findings of perfect time-sharing in Hazeltine et al. (2002) without eliminating the bottleneck (Anderson, et al., 2005). If it is the case that response selection can take place at such short durations, it may be very difficult to observe performance limitations associated with a bottleneck through behavioral measures.

This debate has left researchers at somewhat of an impasse; if including a 50 ms bottleneck can result in no significant difference between RTs, then there is no way to rule out a latent bottleneck model with measures of RT alone. As a result, simultaneous onset paradigms that avoid the first issue with timing are susceptible to the criticism that the lack of differences in RT may result from using two tasks with very short response selection stages that do not overlap. In other words, perfect time-sharing with RT measures is not sufficient evidence to rule out a single channel used to select responses.

Evidence from neuroimaging

Although the behavioral evidence for the latent bottleneck comes from studies using the PRP procedure with the instructions emphasizing Task 1 over Task 2, recently, there has been some evidence from functional imaging research by Dux and colleagues to support this view (Dux, Tombu, Harrison, Rogers, Tong & Marois, 2009). Dux et al. (2009) proposed a hypothesis for dual-task coordination in which additional executive control processes beyond those required to execute a single task are initially recruited to coordinate multi-task performance in a dual-task scenario. Results from an fMRI study showed that the left inferior frontal junction (IFJ), situated in between the posterior lateral prefrontal and anterior premotor cortex, was much more active on dual-task trials than on single-task trials before practice. The authors suggest that an individual's IFJ activity is directly related to performance costs in dual-task situations, and that this region may be the neurological locus of a response selection bottleneck. Practice eliminates, or nearly eliminates, dual-task costs by reducing the dependency on this brain region that seems to be specifically selected for dual-task coordination. As the performance decrements in RT decreased with practice, the difference in activation for the IFJ between dual- and single-task trials was also eliminated. An experiment that measured the duration of neural activity in the IFJ revealed significantly longer durations of activity in the IFJ on dual-task trials versus single-task trials at the start of training, but this difference was also eliminated as the dual-task costs in the behavioral data decreased (Dux et al., 2009). The authors cite this as evidence in favor of the latent bottleneck hypothesis and suggest that practice reduces processing time in the IFJ, thereby leading to significantly reduced dual-task costs in both behavioral and neural measures.

Resource Models

There are several theories of response selection that do not include a structural or functional bottleneck that would give rise to dual-task interference. There is a large body of literature that accounts for dual-task interference by proposing one, or a number of, capacity-limited pools of general cognitive resources necessary for performing response selection tasks. Resource pools can be used in parallel, but when two tasks require use of the same pool, then possessing is slowed, resulting in dual-task costs (see e.g., Kahneman, 1973; Navon & Gopher, 1979; Wickens, Sandry & Vidulich, 1983). According to resources models, serial performance in dual-task situations is not the result of structural limitations; instead, when two tasks require resources from the same pool simultaneously, the resources are allocated in a flexible, graded manner that is contingent on the requirements of each task. As such, resource models allow for parallel processing, but suggest that dual-task costs arise because processing is slowed when two tasks are using the same pool of resources as compared to a single-task situation.

Resource models make many of the same predictions as RSB models as far as *when* dual-task costs will be observed, but they make different claims about *why* dual-task costs arise. One of the biggest differences between the behavioral predictions made by RSB models and resource models is that resource models allow for very efficient dual-task performance so long as the two tasks require independent pools of resources. If the two tasks do not share the same capacity-limiting pool, resource models would predict no dual-task costs.

In a practice study, Maquestiaux et al. (2008; see also, Ruthruff et al., 2006) noted that they observed robust dual-task costs using the PRP procedure when Task 1 putatively did not require the RSB but Task 2 did; however, no dual-task costs were observed when the task order was reversed. They proposed a "greedy resource recruitment" hypothesis, which holds that central operations required for response selection are engaged by a task *regardless* of whether it is actually needed. Thus, if response selection for one task is performed first, it may "greedily" engage resources needed for the second task, producing otherwise avoidable dual-task costs. In short, to minimize dual-task costs it is more important that the second task not require many resources or occupy central processing components than the first. Even when the stimuli are presented simultaneously in dual-task blocks, (see e.g., Halvorson et al., 2012) and the experiments do not have a pre-assigned "Task 1" and "Task 2" – it is possible that participants strategically choose to perform one task before the other even if "Task 1" is relatively easier.

In general, resource models can account for many dual-task findings because of the flexibility that is built in to reflect situational factors like strategy and the particular task pairings. As a result of this flexibility, the main significant limitation to resource theories is that there is no independent way to measure a resource. Resources are said to be limited-capacity and general, and when two tasks require the same pool then there are dual-task costs. When there are no dual-task costs, then the tasks use different pools. By defining a research pool by whether or not costs are observed, there is no way to independently measure how many pools of resources there are or predict when they will be required by a certain task (see e.g. Meyer & Kieras, 1997; Hazeltine et al., 2006). Wickens (1984) proposed perhaps the most comprehensive resource model, by identifying three components of the tasks (i.e., stages, codes, and modalities) that must use distinct resources in order to avoid dual-task interference. However, even this model is susceptible to the critics' claims that resources are only identifiable once it has been determined whether or not there are dual-task costs.

Crosstalk

According to some multiple-pool resource theories, because parallel processing is likely occurring during multi-task situations, in addition to an overall reduced rate of processing, a phenomenon called crosstalk or output conflict may be exacerbating dual-task costs (Navon & Miller, 1987). Navon and Miller (1987) suggest that parallel processing can cause the two tasks to interact in such a way that leads to difficulty parsing the demands of one task from the other. This interaction between tasks results in a type of interference known as crosstalk. Crosstalk is the output conflict that occurs when some aspect of one task changes the state of a variable that is relevant for performance on the concurrent task (Navon & Miller, 1987). In other words, a major source of dual-task interference comes from participants' inability to completely separate the processing required of one task from the processing of the other. For example, if both tasks use stimuli from semantically related categories, activating two conceptually related representations at the same time creates crosstalk. Navon and Miller (1987) dissociated the effects of crosstalk from competition for resources by showing increased dual-task costs when there was more crosstalk between the two tasks and overall difficulty was kept constant. Dual-task interference, therefore, cannot result exclusively competition for a common pool of resources. Because of the difficulty that arises during situations with a great deal of crosstalk, Navon and Miller (1987) suggested that participants often voluntarily adopt a serial strategy to avoid output conflict. As such, resource models predict patterns of results that reflect serial performance when there is a lot of crosstalk, but suggest that it comes from strategic limitations instead of structural.

Strategic models

The hypothesis that participants might strategically respond in a serial manner was also adopted by a theory of executive functioning known as the executive-process interactive control (EPIC) architecture. EPIC is a comprehensive architecture used for computationally modeling behavior in various executive control tasks, including multi-tasking behavior. EPIC has perceptual processors, responsible for transmitting visual, auditory, and tactile information to working memory, that provide direct lines for sensory information to working memory. EPIC also has motor processors that receive inputs from working memory that contain abstract information about the response to be made which they then transform into output commands that actually control simulated physical effectors (e.g., the index finger on the left hand). In order to give working memory the codes to send to the motor effectors which select the appropriate response, EPIC uses a domain-general cognitive processor that creates what are called production rules. Production rules are abstract, symbolic strings of items for a given task and refer to very simple notes, steps and goals stored in working memory. Production rules are programmed based on the perceptual information associated with the task, and they are used to update the contents of working memory when steps have been completed, and to order the execution of motor commands to meet the specific task goals.

Importantly, EPIC allows for parallel processing within the cognitive processor. The cognitive processor has the ability to make progress on several tasks at a time; the behavioral results associated the PRP task in which large dual-task costs are observed are attributed primarily to different strategies for scheduling the tasks that can be determined by the participant depending on the situation. In some PRP tasks, when there is one task that is always presented first and is always supposed to receive priority, EPIC can accurately model human behavior by choosing a “lockout scheduling” strategy. Lockout scheduling involves a supervisory system that completely suspends processing on one task until the previous task has been completed. The advantage of this type of schedule is that it is simple to execute and does not require and the processing required for each task is much like that required for a single task. Importantly, the serial nature of performance under this type of schedule is optional, as opposed to the structural limitations proposed by RSB models.

EPIC is capable of other scheduling strategies for multi-task behavior, such as interleaved scheduling, in which the production rules required for completing the two tasks are highly dependent on relationship between the two tasks. In this type of scheduling, both tasks are processed in parallel, except during short, minimal time periods in which concurrent processing would lead to conflict. During times of conflict, processing of one task is paused while the system is focused on the other. Meyer and Keiras (1997) have suggested that the role of practice in situations of perfect time-sharing is to allow the central processor to shift from lockout scheduling to interleaved scheduling. According to EPIC, in most dual-task situations, decrements to RT would arise from strategic, voluntary, momentary suspension of processing on one task, known as lockout scheduling, so that some aspect of the other task, usually movement selection, can proceed without interference.

Why are minimal dual-task costs important?

In general, researchers believe that by loading the mechanisms responsible for response selection, we can illuminate the processes by which humans select and execute the correct actions. Establishing whether response selection can occur in parallel is an important part of explicating these mechanisms. Given that many models of response selection make strong claims as to whether or not structural limitations prevent parallel processing, researchers often focus on finding conclusive evidence of a zero millisecond difference between single- and dual-task RTs. Such a difference, or lack thereof, is therefore theoretically important and has caused researchers to consider even small dual-task costs as evidence in favor of the structural bottleneck. As Ruthruff et al. (2003) state, “we argue that researchers should focus not just on the practical issue of whether the observed bottleneck delay is large or small, but on the deeper theoretical issue of whether the underlying processing limitations have been eliminated” (p. 281).

However, given the difficulty of detecting a very short bottleneck stage, a zero millisecond difference between conditions has been shown to have limited explanatory power, and disregarding the “practical” issue of the observed delay has caused the factors that resulted in greatly reduced, albeit significant, dual-task costs to be relatively ignored. In the work presented here, I will focus on factors that lead to significant changes in the magnitude of the dual-task costs using different measures of single- and dual-task performance and various task pairings. Unlike Ruthruff et al. (2003), I do not believe the issue of whether the observed delay is large or small is merely a practical one. Given that most dual-task studies result in large costs (i.e. a magnitude of 100 ms or greater) *despite* the variability in performance caused by individual differences and aspects of the task structure, situations that consistently show minimal dual-task costs (even if they are greater than 0 ms) have important implications for our understanding of response selection.

The aim of these studies is to investigate why particular combinations of tasks result in greatly reduced performance costs compared to costs typically associated doing two things at the same time. So even if a demonstration of perfect time-sharing with two IM-compatible tasks does not conclusively rule out a response selection bottleneck, characterizing interference according to factors associated with task structure and task pairings will aid in our understanding of dual-task performance and response selection. To this end, I will focus on how the context in which the tasks are being performed and the relationship between the two tasks can illuminate the locus of interference by comparing the relative magnitude of the costs across experiments in which these things are manipulated.

Findings of efficient dual-task performance

Compared to the robust findings of large dual-task costs, only a very small number of studies have demonstrated that two tasks can be performed concurrently with minimal cost to either task (e.g., Greenwald & Shulman, 1973; Schumacher et al., 2001; Hazeltine et al., 2002). Unfortunately, many of the findings of dramatic reductions in dual-task costs to date require either a great deal of practice or a great deal of surgery. In some cases, moderate amounts of practice have been shown to produce highly efficient dual-task performance (Schumacher et al., 2001; Hazeltine et al., 2002). Hazeltine et al. (2002) used two tasks in which none of the stimulus or response modalities overlapped to study the effects of practice on dual-task costs. Participants made a vocal response to an auditory stimulus and a manual button press to a visual stimulus in single-task and dual-task blocks. After 8 sessions, or roughly 4000 trials, there were no significant dual-task costs for either task. Follow-up studies showed that increasing the difficulty of the stimulus-response (S-R) mapping and increasing the complexity of the visual stimuli slowed responses in the AV task slightly but did not alter the main pattern of results.

Under the right task conditions, split-brain patients who have had their corpus callosum severed can perform two tasks concurrently without much practice and without incurring dual-task costs (Hazeltine, Weinstein & Ivry, 2008). In this study, patients whose hemispheres were no longer connected were able to make two manual responses independently on the same trial as compared to controls of roughly the same age. Unlike the controls, whose responses were susceptible to compatibility effects and showed greater evidence of response grouping, the split-brain patient appeared to be able to execute two responses simultaneously without much evidence of one response affecting the other.

Only a few studies have shown essentially no dual-task costs with neurologically intact participants in the first session with little to no practice. In such cases, the stimulus-response (S-R) mappings may allow participants to choose the correct response in such a way that the functional or anatomical structures that typically causes dual-task costs to arise can be avoided (Greenwald & Shulman, 1973). These studies use stimuli and responses that are highly compatible in a particular way that is consistent with the principles of Ideomotor (IM) theory. These tasks allow for a more direct comparison with other unpracticed, dual-task experiments that are known to cause significant performance impairments in neurologically intact participants. The similarity between these scenarios may allow for stronger claims about what factors limit dual-task performance.

Ideomotor-compatibility and dual-task performance

IM theory holds that motor movements are represented as and can be accessed by their sensory feedback, or the effects they produce in the environment (Greenwald & Shulman, 1973; Hommel et al., 2001; Prinz, 1992). That is, actions are selected based on the desired environmental outcome. IM-compatible S-R mappings involve stimuli that strongly resemble the sensory consequences of their associated responses. In highly compatible cases, or when the stimulus is nearly identical to the environmental effect of the required response, participants can directly access the appropriate response when presented with the stimuli, which seems to avoid the performance limiting processing stage. Vocal shadowing is a good example of an IM-compatible task; when participants are asked to repeat a spoken word, the perceptual outcome of the action is nearly identical to the stimulus.

Greenwald and Shulman (1973) reported an experiment that used two classes of tasks, one involving IM-compatible S-R mappings and one involving S-R mappings that were not specifically IM-compatible, but were still highly compatible. For the IM-compatible tasks, there was a visual-manual (VM) task with directional arrows (left or right) that required a manual response of shifting a joystick in the corresponding direction and an auditory-vocal (AV) task in which the letters “A” or “B” were presented aurally and required shadowing. For the S-R compatible tasks, the VM task consisted of visually presented words “left” and “right” that required manual movements of the joystick to the left or right and an AV task with the same stimuli, but the required vocal responses were “one” or “two.” Four groups of participants were run in a 2 x 2 between-subjects design, in which one axis represented whether the AV task was S-R compatible or IM-compatible, and the other axis represented whether the VM task was S-R compatible or IM-compatible.

The researchers used the psychological refractory period (PRP) procedure in which two stimuli are presented in succession with varying stimulus onset asynchronies (SOAs) and participants are asked to make a separate speeded response to each task (e.g., Smith, 1967; Welford, 1952). An increase in VM RTs as SOA decreased – the so-called PRP effect – was observed for all four groups. When the VM task was IM-compatible, RTs were significantly shorter than when the VM task used pairings that were merely S-R compatible, although the magnitude of the PRP effect was not significantly affected by whether the VM task was IM-compatible. In contrast, the type of task used for the AV task significantly affected both the AV RTs and the magnitude of the PRP effect.

However, there were also effects of SOA on the AV RTs, which complicates the interpretation of both the AV and VM RTs. In contrast to the VM RTs, the AV RTs were shortest at the shortest SOA and longest at the longest SOA. In light of this trade-off, the authors averaged RTs across the two tasks for each trial. When examined this way, RTs were not statistically different at the 0ms SOA and the 1000ms SOA when both tasks were IM-compatible. This is the only condition for which this was true; there was a significant difference between RTs at the 0ms SOA versus the 1000ms SOA for both conditions where only one of the tasks was IM-compatible, and an even larger effect when both tasks used S-R compatible pairings.

A second experiment by Greenwald and Shulman (1973) used instructions in which participants were told that the two tasks would often appear at the same time and they were not explicitly told to prioritize either task. The stimuli appeared only at 0, 100, 200, or 1,000ms SOAs. With these changes, the PRP effect was significant for the all three conditions involving at least one S-R compatible mappings, and the conditions with just one task IM-compatible task showed significantly smaller PRP effects than the condition in which both tasks were S-R compatible. For the condition with two IM-compatible tasks, there was no effect of SOA. Thus, it appeared that changing the instructions allowed for highly efficient dual-task performance of two IM-compatible tasks.

If IM-compatible stimuli allow humans to make responses in such a way that dual-task costs can be avoided, there are far-reaching implications for our understanding of how such responses are selected. That is, instances in which dual-task costs are dramatically reduced shed light on some of the underlying cognitive mechanisms associated with response selection, particularly if it is possible to achieve perfect time-sharing in a single session with little or no practice. Moreover, the concept of IM-compatibility converges with recent developments in the study of interactions between perception and action, including the theory of event coding (Hommel et al., 2001) and theories of embodiment (e.g., Barsalou, 2008). A better understanding of the phenomenon may strengthen the links between these theoretical frameworks and help establish an embodied account of response selection. These issues will be taken up subsequently.

Controversy over IM findings

The notion that IM-compatibility eliminates dual-task costs has proven controversial. Lien, Proctor, and Allen (2002) attempted to replicate the perfect timesharing reported in Greenwald and Shulman (1973) in four experiments, but each experiment produced a significant PRP effect, including a near-exact replication of Greenwald and Shulman's (1973) Experiment 2. The authors concluded that processing limitations persist during dual-task performance, even with IM-compatible stimuli.

These discrepant findings sparked several studies by Proctor and colleagues (Lien, Proctor & Ruthruff, 2003; Lien, McCann, Ruthruff & Proctor, 2005; Shin, Cho, Lien & Proctor, 2007; Shin & Proctor, 2008) and Greenwald (Greenwald, 2003; 2004; 2005) examining the necessary conditions for eliminating dual-task costs with IM-compatible tasks. To date, most of the debate has centered on methodological differences, such as whether the required response was a joystick movement or button press, whether the arrows were presented centrally or slightly offset to the left or right, and how participants were instructed to respond (Lien et al., 2002; Greenwald, 2003; Shin et al., 2007; Shin & Proctor, 2008). All of the experiments reported here use button press responses and do not use arrows as the VM stimulus, so many of the methodological issues raised previously are not relevant. However, factors known to affect dual-task performance, such as the way participants are instructed to respond and what the appropriate single-task trial is to use as a baseline, influenced performance even when two IM-compatible tasks were used.

As Greenwald (2003) points out, RTs are significantly faster when instructions stress speed and simultaneity of responding as opposed to the traditional PRP instructions which stress prioritization of Task 1. To demonstrate this, Greenwald (2003) performed an experiment that contained blocks with the traditional PRP instructions and range of SOAs as well as blocks that consisted entirely of 0ms or 1000ms SOA trials and instructions emphasizing speed and simultaneity of responding as the only dual-task blocks. In the 0ms SOA blocks, stimuli were presented simultaneously on every trial, allowing participants to respond quickly. Furthermore, for these blocks, Greenwald eliminated the instructions that encouraged participants to prioritize one task over the other. As a result, participants responded significantly faster in the condition with simultaneous instructions and only two SOAs than in the PRP condition. Moreover, the PRP condition revealed significant dual-task costs: RTs were 34 ms slower in the 0ms blocks than in the 1000 ms blocks. In contrast, there was no difference between the 0 ms and 1000 ms blocks when they were the only two block types and the prioritization instructions were eliminated. This shows that aspects of task structure known to affect dual-task performance, such as instructions about task prioritization and the range of SOAs, significantly altered the pattern of results even with two IM-compatible tasks.

Halvorson, Ebner & Hazeltine (2012)

Halvorson, Ebner and Hazletine (2012) used IM-compatible stimuli to directly test how a variable SOA and different measures of single-t ask performance affect the magnitude of dual-task costs. Previous findings demonstrate that block types, number and range of SOAs, and instructions affect dual-task costs (Greenwald, 2003; Tombu & Jolicouer, 2004). To measure the effects of these components independently, we compared three measures of single-task performance: pure single-task blocks (e.g., Schumacher et al., 2001), OR blocks (e.g., Greenwald, 2003; Tombu & Jolicouer, 2004), and long SOA trials in dual-task blocks within the PRP procedure (e.g., Pashler, 1994).

For this experiment, the tasks were modeled after Greenwald and Shulman's (1973) original task. Arrows indicating either a left or a right response were used as the visual stimuli, and participants were required to make a left or right keypress in response. For the auditory task, participants were required to say the name of the letter that was presented through a headset ("A" or "B"). SOAs of 0, 200 and 800 ms were used.

A significant mixing cost was observed for the VM task (Task 2). In other words, participants' RTs were longer as a result of preparing for two task sets, even when they only saw one stimulus and made one response on a given trial and both tasks were IM-compatible. We also observed robust dual-task costs, which was measured independently of mixing costs by comparing RTs at the shortest SOA in the PRP blocks to RTs at the shortest SOA in the OR blocks. Consistent with typical PRP experiments, Task 1 RTs were relatively unaffected by the presence or absence of Task 2 and SOA was only a factor in the OR and PRP blocks. This suggests that participants were adhering to task instructions, which emphasized responding to Task 1 as quickly as possible, without letting Task 2 interfere. In contrast, robust dual-task costs were observed for Task 2. In sum, the pattern of dual-task costs was nearly identical to previous PRP tasks showing dual-task costs with IM-compatible tasks (e.g., Lien et al., 2002), even when RTs from the OR blocks were used as a measure of single-task performance.

While we obtained three distinct measures of single-task performance, the 0 ms SOA trials during the PRP blocks were the only measure of dual-task performance. However, the literature offers two widely-used measures of dual-task performance: short SOA trials in blocks based on the PRP trials (e.g., Pashler, 1994) that we examined in Experiment 1 and simultaneous presentation trials in which stimuli for the two tasks appear either simultaneously or separated by a long interval (e.g., Schumacher et al., 2001). Note that the trials used to derive these measures can be identical in terms of the timing of events if a 0 ms SOA is used in the PRP trials. However, it is not possible to include both of these types of trials in a within-subjects design, because the instructions in the PRP procedure require participants to prioritize one of the tasks, and this can produce carry-over effects on the simultaneous presentation blocks, in which participants are instructed not to prioritize either task. Therefore, in Experiment 2, we used only the simultaneous measure to compare to the measure of dual-task performance obtained with the PRP procedure in Experiment 1.

In Experiment 2, we eliminated the instructional manipulation that required participants to prioritize the AV task and presented both stimuli simultaneously on all trials in the AND blocks. We included the OR blocks to look at the effect of mixing costs on dual-task performance even when both stimuli are presented simultaneously on the dual-task trials. We used the exact same stimuli as in Experiment 1.

The results indicated that dual-task costs can be nearly eliminated with IM-compatible tasks. For ten of the twelve participants, the mean RT on the dual-task (AND) blocks were within 7 ms of the mean RT of the single-task blocks and, if anything, a slight negative dual-task costs for these participants when you compare AND RTs to mean RTs from the OR blocks. There was also little evidence of mixing costs. Furthermore, the data, in combination with those from Experiment 1, support the proposal put forth by Schumacher et al. (2001) and Greenwald (2003) that simultaneous presentation of the stimuli greatly facilitates efficient time sharing. That is, it appears that dual-task costs can be dramatically reduced, or even eliminated, with the same stimuli that were used in Experiment 1 so long as both stimuli are presented at the same time and participants were not told to prioritize either task.

Controversy over arrows

Although the tasks used in Experiment 2 did not show evidence of dual-task costs, it is not entirely clear that the visual-manual task used meets the criteria of IM-compatibility as established by Greenwald and Shulman (1973). As Lien, Proctor and Allen (2002) point out, the term “IM-compatible” has been applied to many different tasks, yet the only widely-used visual-manual pairing in experiments purporting to examine IM-compatibility is an arrow signaling a manual response corresponding to the direction of the arrow. It is not obvious that an arrow is the best instantiation of an IM-compatible stimulus, given Greenwald and Shulman’s (1973) formulation: stimuli are IM-compatible to the extent that they resemble the sensory feedback of the associated response. Although humans have extensive experience with arrows and arrows clearly indicate a direction, it is not obvious that arrows are commonly experienced as an environmental consequence of making a movement to the left or right.

To address this, Halvorson et al. (2012) used images of a human hand (from the perspective of an individual looking at his or her hand) as the visual stimuli for the VM task. We used these images because they likely reflect some aspect of the sensory feedback one might experience following a manual button press more than an arrow reflects the sensory feedback associated with moving a joystick. These stimuli allow for the added benefit of using manual keypresses as the responses for the VM task and avoiding the controversy surrounding the joystick response device (e.g., Shin & Proctor, 2008). Moreover, because these images are of a body part, using them as examples of IM-compatible stimuli is strongly in keeping with the principles of embodied cognition.

Embodied cognition emphasizes the importance of bodily movement, environmental context, and the action-relevant information in the perceptual display in cognitive tasks (see e.g., Wilson, 2002; Barsalou, 2008). Embodied theorists reject the notion that there is a significant amount of translation or processing between the onset of the stimulus and the production of the response; instead, embodied researchers claim that all cognition is deeply grounded in the body's interactions with the environment and that responses are elicited by the physical properties of items in the environment (Barsalou, 1999). Grounded cognition also implies that all cognitive processes operate in a fluid and dynamic manner. This suggests that the constant influx of perceptual information humans receive affects the way information is processed in the environment, which means that motor activity is executed in accordance with the current task-relevant stimulus parameters (Wilson, 2002). In keeping with these principles, the image of a hand may allow participants to avoid dual-task costs when paired with a second task because images of body parts in particular would require very little processing or translation and may even have a special or privileged pathway to the desired response.

Thus, in Experiment 3, we examined whether dual-task costs were observed with a visual-manual task using stimuli that are more visually complex and arguably less spatially compatible, but better fit the definition of IM-compatibility; that is, the stimuli depict some aspect of the sensory consequences of the appropriate response. In this way, we directly tested the IM-compatibility account: do tasks with stimuli that resemble the perceptual consequences of the appropriate responses produce minimal dual-task costs?

The results of Experiment 3 were mostly consistent with those of Experiment 2 and Greenwald and Shulman (1973); although mixing costs were reported for both the AV task and the VM task, dual-task costs were either absent or relatively small for both tasks. Experiment 3 extended previous IM findings by using novel IM-compatible stimuli for the VM task that closely adhere to the definition of IM-compatibility. However, there were some indications of small dual-task costs. We used the same criterion as in Experiment 2 to look for individual differences in dual-task costs, but none of the participants showed costs greater than three times the standard deviation of the mean dual-task cost. When the pure, single-task trials served as a baseline, there was a small dual-task cost for the VM task. It may relate to competition for central resources – the traditional explanation for dual-task costs – or it may relate to differences in the number of S-R mappings that need to be maintained in WM or the greater uncertainty about the particular combination of stimuli that might appear on a given trial. Importantly, even though the cost was significant, the magnitude of the dual-task cost reported here is relatively small (36 ms for the AV task and 20 ms for the VM task). Moreover, the costs were not apparent when the OR blocks were used as baseline to correct for the number of S-R alternatives. In fact, the OR blocks produced significantly longer RTs than the single-task blocks (i.e., there was a robust mixing cost), suggesting that the dual-task costs may arise from something other than competition for central resources. These issues were taken up in subsequent experiments.

Table 1. Summary of Experiments 2-6 from Halvorson et al. (2012).

Experiment	AV Task Single	AV Task OR	AV Task AND	VM Task Single	VM Task OR	AV Task AND	*R* AND
Exp. 2 IM2-IM2(A)	391	406	400	443	457	476	.698
Exp. 3 IM2-IM2	357	389[s]	393[s]	474	522[s,a]	494[s]	.574
Exp. 4 IM4-IM4	369	384	423[o,s]	532	582[s,a]	558	.367
Exp. 5 IM2-AM2	397	394	424	472[o]	449	553[s,o]	.778
Exp. 6 AM2-IM2	505[o]	448	620[s,o]	495	483	696[s,o]	.651

Note: Table includes mean RTs for each block type and mean r value for the RT1 – RT2 correlation from each experiment from Halvorson et al., (2012). The experiment number is followed by the types of task used for AV task and VM task. IM = ideomotor compatible; AM = arbitrary mapping, followed by the number of S-R alternatives. (A) indicates that arrow stimuli were used instead of hand stimuli. [s] indicates that the condition was performed significantly more slowly than the corresponding single-task condition. [o] indicates that the condition was performed significantly more slowly than the corresponding OR condition, and [a] indicates that the condition was performed significantly more slowly than the corresponding AND condition. All subjects are included in these estimates.

Experiment 4 required participants to respond to four S-R pairings for each of the tasks. The Hick/Hyman law (Hick, 1952; Hyman, 1953) states that increasing the number of S-R pairings should cause an increase in RTs; as such, this manipulation been used in previous dual-task studies to increase task difficulty, (e.g., Van Selst & Jolicoeur, 1997; Pashler, 1994; Karlin & Kestenbaum, 1968) even when there is little overlap between input and output modalities. If single-task RTs increase for both tasks, many models predict that increases in AND block RTs should be greater than the increases in the other block types for at least one of the tasks. This is predicted because the RTs for dual-task trials include the duration of central operations of both tasks, which is thought to be affected by task difficulty. However, the data did not confirm this prediction. Although the single-task RTs for the VM task in Experiment 4 were significantly slower than in Experiment 3, increasing the number of S-R pairs did not significantly change the pattern of results for the mixing or dual-task costs. Once again, comparing RTs from the OR blocks to RTs from the single task blocks revealed significant costs to performance as a result of task uncertainty. Although there was a small dual-task cost for the AV task when RTs from the AND blocks are compared to RTs from the single task blocks, the overall pattern of results was similar to Experiment 3 (Table 1).

Increasing the number of S-R alternatives from two to four did not significantly change the pattern of results, suggesting that the differences in RT between the single-task and AND blocks did not stem from competition for central response selection processes. At this point, it seemed as though IM-compatible tasks may in fact bypass central response selection mechanisms typically assumed to cause dual-task costs. If that is the case, then only one IM-compatible task should be required to avoid dual-task costs. So long as one of the tasks in the pairing does not require the use of central response selection mechanisms, a second task that requires translation should be able to be performed simultaneously. The goal of Experiments 5 and 6 was to test this prediction. To do this, we reverted to two-choice tasks for both the AV and the VM tasks; however, only one of the tasks was IM-compatible and the other was arbitrary. An arbitrary VM-task (a color patch arbitrarily mapped to one of the two responses) was paired with the IM AV task (Experiment 5), and an arbitrary AV-task (a high and low tone arbitrarily mapped to the vocal responses “cat” and “dog”) was paired with the IM VM task (Experiment 6). If IM-compatible tasks simply bypass the central-response mechanisms responsible for slowing performance when two responses are required, then minimal dual-task costs should be observed in both of these experiments.

The data did not confirm this prediction; significant dual-task costs were observed in Experiments 5 and 6. If there are direct links between sensory depictions of the action and the production of the action then one IM-compatible task should be sufficient to nearly eliminate dual-task costs, because the use of these automatic links should eliminate competition between the two tasks (McCleod & Posner, 1984; Barsalou, 1999). Instead, dual-task costs and RTs were the largest when the VM task was arbitrary and the AV task was IM-compatible. While some stimuli may activate some responses more efficiently than other pairings, these results do not support the notion of specialized links that can be exploited to avoid taxing central resources. Instead, the absence of dual-task costs appears to rely on the *combination* of tasks. Thus, the overall task structure that emerges from the pairing of the two particular tasks appears to be imperative in understanding when dual-task costs arise. These findings suggest that both tasks must be IM-compatible in order to avoid dual-task costs.

Why do two IM tasks dramatically reduce costs?

Halvorson et al. (2012) showed that one IM-compatible task was not sufficient to eliminate dual-task costs. A strict interpretation of RSB models would be in conflict with the findings from Halvorson et al. (2012) assuming dual-task costs are eliminated because IM-compatible tasks do not engage the response selection processes that form the RSB. If that were the case, then a single IM-compatible task should be sufficient to eliminate dual-task costs. That is, as long as one of the tasks does not require the bottleneck, both tasks should be able to proceed in parallel. Why, then, are robust dual-task costs observed with one IM-compatible and one arbitrary mapping task? Note that the same pattern was observed in the original Greenwald studies (Greenwald & Shulman, 1973): only when both tasks were IM-compatible were dual-task costs not observed. The bottleneck model can account for these findings if it is assumed that pre-bottleneck operations are shorter and bottleneck operations are longer for the VM task in Experiment 5 than for the VM task in Experiment 4. In other words, the color discriminations required by the VM task in Experiment 5 may require less time than finger discriminations required by the VM task in Experiment 4. Because the two tasks produced similar RTs, it is necessary to further assume that the central operations take less time for the VM task in Experiment 4 than the VM task in Experiment 5. This assumption is reasonable given that the mapping was IM compatible in Experiment 4 and arbitrary in Experiment 5.

Such an explanation is plausible, but some limitations should be noted. First, given that the PRP procedure can induce costs that are not apparent when the stimuli for the two tasks are consistently presented at the same time (Schumacher et al., 2001; Israel & Cohen, 2011; Halvorson et al., 2012), the durations of pre-bottleneck and bottleneck stages are difficult to independently verify. Second, the magnitude of the costs suggests that the duration of response selection operations for the IM-compatible AV tasks was not trivial (i.e., on the order of 100 ms), which is inconsistent with other accounts of near-perfect dual-task performance (e.g., Anderson et al., 2005). Third, if the VM task engaged response selection operations before the AV task in Experiment 5 but not in Experiment 4, RTs for the AV task in the AND blocks should be much slower in Experiment 5 than in Experiment 4 in Halvorson et al. (2012). However, follow-up analyses showed that the difference in the AV RTs across the AND blocks for the two experiments was not significant, $t<1$. Moreover, there should have been robust dual-task costs on the AV task in Experiment 5, but these were small (e.g., 30 ms) and, depending on the measure, either only marginally significant or not significant. Thus, it would be necessary to further assume that the AV task was prioritized in Experiment 5 and both tasks require the central bottleneck. In order for the findings to not rule out or highly constrain bottleneck accounts of dual-task performance, then they would require an alternate explanation of how responses are selected in an IM-compatible task.

Although the findings from Halvorson et al. (2012) make Greenwald and Shulman's (1973) original claims about IM-compatible tasks bypassing response selection mechanisms untenable, and challenges strict bottleneck models of response selection, the question of why two IM-compatible tasks show such dramatic reductions of dual-task costs remains unresolved. To date, very few studies have examined dual-task performance with IM-compatible tasks, and within those studies even fewer changes have been made to the S-R pairs used for each task; these experiments are described in Table 2.

Given the limited variability of tasks used in IM-compatible dual-task experiments to date, subsequent experiments will systematically manipulate the stimuli (while keeping the response constant) in order to investigate the relationship between task pairings and the magnitude of the dual-task interference. Changing the stimuli but leaving the responses constant allows me to control for the possibility that some responses require more resources to produce and instead focus on how subtle changes to S-R pairs affects the relationship between the tasks and the amount of interference. Each chapter will examine a specific hypothesis or set of hypotheses that could account for the dual-task findings with IM tasks to date.

Overview of Chapters

The aim of Chapter 2 is to establish the phenomenon of dramatically reduced dual-task costs with two IM-compatible tasks. In addition to replicating previous findings with two IM-compatible tasks, a second aim is to establish a baseline measure of dual-task interference using similar (but non-IM) tasks for the paradigm used in Halvorson et al. (2012) which will also be used in all subsequent experiments. Although simultaneous presentation and the use of multiple measures of single-task performance have been used previously in dual-task experiments, the specific task structure established in Halvorson et al. (2012) is not commonly used in dual-task experiments. Therefore, an experiment with the exact same timing, order of events, and responses with AV and VM tasks that have an arbitrary relationship will be run for the purposes of comparing the changes in dual-task costs based on task pairings.

Once these baselines have been established, Chapter 2 will set up the four primary hypotheses that could account for the previous data. Chapter 3 will test the *automatic activation hypothesis* by changing the S-R mappings without making any changes to the stimuli and responses.

Table 2. Description of dual-task studies using IM-compatible tasks.

Paper/ **Experiment**	Design	Average Dual-task Costs (ms)	AV S (R)	VM S (R)	AV Single RT (ms)	VM Single RT (ms)
Greenwald & Shulman (1973) **1**	PRP	16	“A” “B” (“A” “B”)	↙ ↘ (Move switch left or right)	300*	375*
Greenwald & Shulman (1973) **2**	PRP (fewer SOAs)	-12	“A” “B” (“A” “B”)	↙ ↘ (Move switch left or right)	350*[s]	400*[s]
Lien, Proctor & Allen (2002) **1**	PRP	70	“A” “B” (“A” “B”)	← → (Move joystick left or right)	560*	490*
Lien, Proctor & Allen (2002) **2**	PRP (fewer SOAs)	50	“A” “B” (“A” “B”)	← → (Move joystick left or right)	545*	470*
Lien, Proctor & Allen (2002) **3**	PRP (fewer SOAs)	60	“A” “B” (“A” “B”)	← → (Move joystick left or right)	504*[s]	515*[s]
Lien, Proctor & Allen (2002) **4**	PRP (fewer SOAs)	34	“A” “B” (“A” “B”)	↙ ↘ (Move joystick left or right)	440*[s]	441*[s]
Greenwald (2003) **1**	0 ms SOA	-2	“A” “B” (“A” “B”)	↙ ↘ (Left – Right Keypress)	398[s]	269[s]
Greenwald (2003) **2**	0 ms SOA, Mixed blocks	13	“A” “B” (“A” “B”)	↙ ↘ (Left – Right keypress)	349[s]	273[s]
Lien, McCann, Ruthruff, & Proctor (2005) **4**	PRP	52	“left” “right” (“left” “right”)	← → (Move joystick left or right)	525	422

Table 2. Continued

Shin, Cho, Lien, & Proctor (2007) **1**	PRP	12	“A” “B”	← →	389	272
			(“A” “B”)	(Left – Right keypresses)		
Shin, Cho, Lien, & Proctor (2007) **2**	PRP	8	“A” “B”	← →	35	299
			(“A” “B”)	(Left – Right toggle switch)		
Shin, Cho, Lien, & Proctor (2007) **3**	PRP	37	“A” “B”	← →	435	287
			(“A” “B”)	(Left – Right keypresses)		
Shin & Proctor (2008) **1**	PRP	70	“A” “B”	(Move joystick left or right)	550*	480*
			(“A” “B”)			

Note: * indicates that the RTs were estimated based off of figures. [s] indicates the single task RTs came from separate single task blocks. Average dual-task costs were calculated (following Greenwald & Shulman’s (1973) logic) by taking the average RT for both tasks at the longest SOA minus the average RT at the shortest SOA.

The new mappings, in which participants will be required to make the opposite response to what is seen or heard, will also test the *task coherence hypothesis*. Importantly, these two hypotheses make opposing predictions about the magnitude of the dual-task interference for these task pairings.

Chapter 5 will test the *task set confusion hypothesis* by maximizing the separability of the task sets for the two tasks in attempt to alleviate binding issues that may be causing interference in the task pairings typically used in arbitrary S-R mappings. According to this hypothesis, when there is a high amount of correspondence within the task sets, and the stimuli for one task do not activate the response set for the other, dual-task interference will be minimal. Chapter 6 will propose a new hypothesis called the *central code crosstalk hypothesis*. This hypothesis also emphasizes the separability of the tasks, but makes novel claims about the sources of dual-task interference including the central codes needed to bind the stimuli to the responses.

In addition to providing separate measures of mixing and dual-task costs, the design used in these experiments allows for comparisons to be made at a an even more fine-grained level which will be described in Chapter 7. Comparing trials from the OR blocks in which the trial type changed (e.g. required a vocal response when the previous trial required a manual response) to trials from the OR block in which the trial type stayed the same (e.g. the current trial required a vocal response as did the previous trial) provides a measure of costs associated only with switching between the two tasks while keeping the cognitive load constant. Furthermore, comparing trials from the OR block in which the trial type stayed the same (but the response alternated) to trials from single task blocks in which the response alternated provides a measure of the effects of cognitive load when the costs associated with switching between tasks is held constant. Breaking the mixing costs down into these two component parts provides insight into the sources of interference that potentially give rise to the mixing costs.

In addition to taking a closer look at mixing costs, the fine-grained analyses in Chapter 7 will examine differences between trial types in the AND blocks. The AND blocks allow for comparisons between complete alternations in dual-task trials (i.e. the S-R pairs for both tasks alternated from the previous trial), partial alternations, and complete repetitions. Two tasks which do not show evidence of overall dual-task costs could show small differences in the magnitude of dual-task costs based on the difference in task pairings compared to the previous trial (this is a measure of the re-binding costs). Although several instances of dual-task performance resulted in minimal overall interference, if there is evidence of re-binding costs it would reinforce the notion that the two tasks are not being processed entirely independently and the importance of considering the task pairings when calculating dual-task interference. Finally, a highly stringent measure of dual-task costs can be calculated using only AND trials in which one or both of the S-R pairs alternated (to eliminate the potential benefit of exact repetition trials) and OR trials in which the task repeated from the previous trial (but the S-R pair alternated) to eliminate the potential contribution of trial type uncertainty to RTs in the OR blocks.

Thus, the fine-grained analyses serve two main purposes; the first is to identify the potential source or sources of mixing costs. The second purpose is to show that even the most stringent measure of dual-task costs reveals a similar pattern of results when compared to coarse measures of dual-task interference to ensure that the minimal dual-task costs observed with the design adopted for these experiments are not purely the result of artifacts like certain trial types leading to very fast RTs (i.e. exact repetitions in the AND blocks) or certain trial types significantly slowing single task RTs used as a baseline (i.e. switch trials in the OR blocks).

In the final summary chapter (Chapter 8) I will review the findings presented here and discuss the ways in which dramatic changes in the magnitude of the dual-task costs arise by making subtle changes to the stimuli and task pairings. I will discuss the ways in which the first three hypotheses fail to account for all the findings and how the *central code crosstalk* hypothesis can accommodate the full range of tasks and interference observed with IM and non-IM tasks in these and previous dual-task experiments. I will return to predictions made by theories of response selection to argue that even bottleneck models that allow for very short central stages cannot accommodate the findings of minimal dual-task costs. Further, I will make predictions as to when dual-task interference will arise based on the evidence collected here, including experiments that tested the boundary conditions of the phenomena and made extensions with regard to when dual-task interference can be reduced. Perhaps most importantly, considerable time will be spent discussing the importance of the task pairings, the constraints of task structure, and participants' conceptualization of the relationship between the tasks when investigating and measuring dual-task interference.

CHAPTER II

ESTABLISHING THE PHENOMENON

The aim of this chapter is twofold: the first objective is to conduct two experiments in order to establish baselines for conditions of significant dual-task interference and highly efficient dual-task performance resulting in minimal dual-task costs. Given the very limited number of findings of such small dual-task costs, the replication will use a larger number of subjects in the exact same paradigm to confirm that the earlier findings were not an artifact of the design or simply due to chance. The dual-task paradigm established in Halvorson et al. (2012) varied in many ways from typical PRP designs commonly used to study dual-task interference. Eliminating the variable SOA, and instructions to prioritize one task over the other, seems to be more conducive to efficient dual-task performance than the typical PRP paradigm. Equating the cognitive load associated with maintaining multiple task sets by using single task trials from OR blocks is also important for obtaining an accurate measure of dual-task interference. However, this particular task structure has not been widely used in the dual-task literature. Thus, it is possible that many simple, 2-choice tasks with distinct input and output modalities may not result in large costs. To test this possibility, Experiment 1 will use two tasks with no relationship between the individual S-R pairs in the exact same paradigm.

Experiment 1: Easy tasks with arbitrary S-R pairs

Although this paradigm is perhaps optimal for efficient dual-task performance, not all task pairings result in minimal dual-task costs with the paradigm used in Halvorson et al. (2012). For example, Experiments 5 and 6 both resulted in large dual-task interference. To obtain an estimate of the dual-task costs for an AV and VM task pairing more comparable to those typically used in dual-task studies, Experiment 1 will examine the magnitude of the mixing and dual-task costs using the paradigm established in Halvorson et al. (2012) with two arbitrary tasks. This experiment will also serve as a point of comparison when making claims about increases or reductions in dual-task costs in subsequent experiments.

Method

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 23) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

Stimuli were presented on a PC computer using the Microsoft Office Visual Basic software. This software recognizes speech and records RT, and auditory stimuli were presented through the earphones on a headset which was also equipped with a microphone that recorded the vocal responses. The stimuli for the AV task consisted of a high (3,550 Hz) and a low (220 Hz) tone lasting 250 ms. The tones were arbitrarily mapped to the vocal responses “cat” and “dog;” mappings were counterbalanced across participants such that there were five participants in each possible combination of mappings. The visual stimuli consisted of the letter “v” or “w” presented in black within a 6.7° by 6.6° neutral colored rectangle, which was framed by a black background. The visual stimuli were presented in the center of the screen. Within the neutral frame, the letter “V” was 3.07° x 3.44° and the letter “W” was 4.99° x 3.44°. The stimuli were arbitrarily mapped to manual responses on the 1 and 2 keys on the number pad with the index and middle finger, respectively. Responses were counterbalanced across participants such that there were four conditions with five participants in each. The visual stimuli were presented on a 19” color LCD monitor that was located approximately 57 cm from the participant.

Procedure

Each participant first completed the voice recognition training on the PC that was used to present the stimuli and collect responses. Following the vocal recognition training, participants were given verbal and written instructions for the AV and the VM tasks. They were told to respond as quickly and accurately as possible in both tasks. Participants were told that each task was equally important, and they were told to make their responses as quickly and accurately as possible. In the AND blocks, they were instructed to do each task as fast as possible and not to prioritize either task.

Each trial proceeded as follows: first, the fixation cross appeared in the center of the screen. The fixation cross was white, 1.3° x 1.3° visual angle, and stayed on the screen for 500 ms. Then the auditory and visual stimuli were presented (a high or low tone, and the letter “v” or “w”) for 250 ms. In the single-task blocks, only one of the stimuli was presented. In the OR blocks, the stimulus presentation was the same, except that the trial order was randomized, and each trial had an equally likely chance of being an AV trial or a VM trial. After 2000 ms or a response, the next trial started.

The experiment consisted of 16 total blocks of trials. Each block type was completed 4 times. The block order, which was the AV task alone, the VM task alone, the OR block and lastly the AND block, was the same for all participants. There were 36 trials per block. The first of each block type was considered practice and eliminated from the final analyses, yielding 544 total trials per participant. Participants were given feedback at the end of each block as to the percent of correct responses made and the average RT for each task.

Results and Discussion

The same criteria were used to eliminate trials and blocks as in the previous experiment. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (10% of the remaining experimental trials) were also eliminated. Overall accuracy was 94%. Mean RTs are plotted according to block type separately for each task in Figure 1.

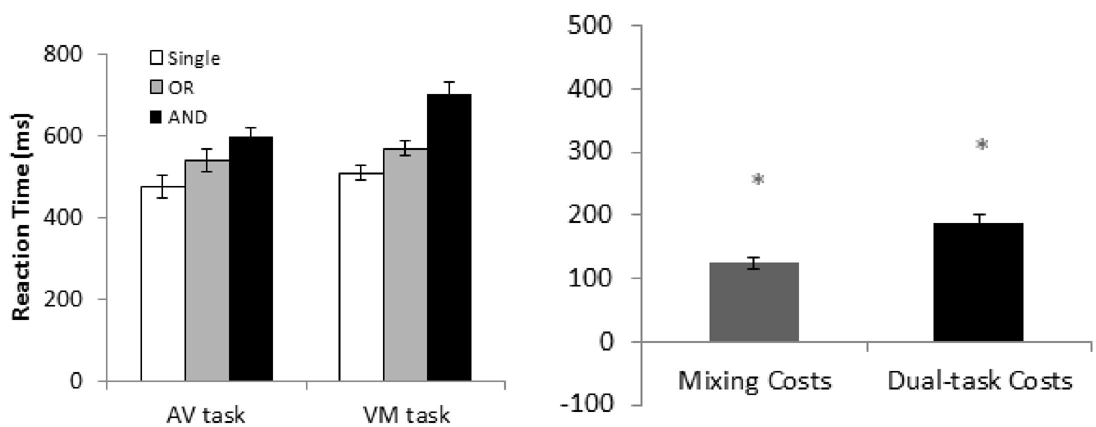


Figure 1. Findings from Experiment 1.
Left panel: mean RTs for each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

The data from each task were submitted to a one-way ANOVA with block-type (single, OR, and AND) as the sole factor. For the AV task, there was a significant main effect of block-type, $F(2,38) = 47.73$, $MSE = 1484.29$, $p<.001$. Response times were 63 ms slower in the OR blocks (540 ms) than in the single-task blocks (476 ms), $t(19)=5.26$, $p<.001$, indicating a mixing cost. The difference between RTs (55 ms) in the OR blocks and AND blocks (595 ms) was also significant, $t(19)=4.46$, $p<.001$ for the AV task.[1] Thus, saying words in response to tones resulted in a significant dual-task cost when paired with the VM task.

A similar pattern was observed for the VM task. The one-way ANOVA with block-type was significant, $F(2,38) = 47.62$, $MSE = 4006.35$, $p<.001$. Once again, the mixing costs were significant; participants were 62 ms slower in the OR blocks (569 ms) than the single-task blocks (507 ms), $t(19) = 7.03$, $p<.001$. The difference between the OR blocks and the AND blocks (487 ms) was also significant (130 ms), $t(19) = 5.52$, $p<.001$. For this task pairing, robust mixing and dual-task costs were observed even though the tasks were relatively simple and used distinct input and output modalities.

Mixing and Dual-task Costs

Although it can be useful to examine the between block comparisons for each task separately, the sum of the mixing and dual-task costs across tasks provides the optimal measure of overall interference. There are many reasons to look at the magnitude of the mixing and dual-task costs summed across tasks. First, the task pairing, or relationship between the S-R pairs for each task, has been repeatedly shown to have dramatic effects on the overall magnitude of the costs (see e.g., Halvorson et al., 2012). For example, even when the responses were the same across conditions, when the IM VM task was paired with the arbitrary AV task using tones as stimuli instead of words, large dual-task interference was observed for both tasks even though the IM VM task showed no dual-task costs when paired with the IM AV task. Importantly, these changes in the magnitude of the dual-task costs based on task pairings make it evident that dual-task performance is not equivalent to doing both tasks separately, but simultaneously. Rather, requiring participants to respond to two stimuli instead of one fundamentally changes the way in which the tasks are processed.

Thus, in order to obtain a clearer the overall magnitude of the between block comparisons described for each task, the sum of the mixing and dual-task costs was calculated across tasks (Figure 1, right panel).

The sum of the mixing costs was 125 ms, $t(19)=6.95$, $p<.001$, and the sum of the dual-task costs was 185 ms, $t(19)=7.27$, $p<.001$. Although the task pairing in the previous experiment also showed significant mixing costs, the difference between the AND and the OR blocks was marginally significant in the opposite direction. Compared to the IM-compatible tasks, the dual-task costs observed here show significant performance decrements for situations in which two responses are required compared to a single response even when the number of S-R pairs being maintained is held constant.

Accuracy

Accuracy for the AV task was 91% and 97% for the VM task. A separate ANOVA with block-type (single task, OR, AND) as a within-subject factor was conducted for each task. The main effect of block-type was significant for the AV task, $F(2,38) = 3.87$, $MSE = .003$, $p<.05$, but was not significant for the VM task, $F(2,38) = 2.43$, $MSE = .000$, $p=.120$. Follow-up t-tests showed that accuracy was significantly higher in the OR blocks (93%) than the AND blocks (88%) for the AV task, $t(19)=3.58$, $p<.01$. Accuracy was not significantly different between single task (90%) and OR blocks, $t(19)=1.87$, $p=.08$, or single task and AND blocks, $t<1$. The consistency in accuracy across block types suggests that the observed pattern of results in RT cannot be solely due to a speed accuracy tradeoff.

Summary

The task pairing in this experiment used two, 2-choice S-R tasks with relatively simple mappings and distinct input and output modalities. This task pairing resulted in robust mixing and dual-task costs. The mixing costs indicate significant performance impairment when cognitive load is increased in spite of the fact that only one response was required on each trial. However, it is likely that both maintaining the stimuli, mappings, and responses for both task sets as well as costs associated with task switching when the current trial used a stimulus from the alternative S-R set as the previous trial, contributed to these costs.

The dual-task costs are dramatically larger in this experiment than in Experiment 3 in Halvorson et al. (2012) even though both tasks were 2-choice, used distinct input and output modalities, as well as the exact same responses. Thus, the minimal dual-task interference observed in Halvorson et al. (2012) does not appear to be an artifact of the design. Although the magnitude of the costs is very consistent with typical performance impairments reported in the dual-task literature, the dramatic *difference* in the magnitude is very surprising given the similarity between these two experiments. In order to replicate findings of minimal dual-task interference and make direct comparisons between experiments, Experiment 2 will use the exact same IM-compatible task pairing as in Experiment 3 from Halvorson et al. (2012).

Experiment 2: Two IM-compatible tasks

The goal of this experiment was to replicate Experiment 3 from Halvorson, Ebner and Hazeltine (2012) with a larger number of subjects and the same IM tasks using images of hands. Because these tasks are novel and there was some indication of dual-task costs in the relatively small (N=12) sample size reported previously, the aim of this experiment is to replicate the initial finding of minimal dual-task costs with the same IM-compatible AV and VM task pairing.

Method

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 23) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus was the same as in Experiment 1. The auditory stimuli were sound files that lasted 250ms and were taken from an internet database. The stimuli used were the words “cat” and “dog”. These words were selected because they are monosyllabic, easily distinguishable, and have no obvious ordinal relationship. The visual stimuli were images of hands making the appropriate key press, although the keypad was not visible. The images used were digital photographs taken of a right hand with either the index or middle finger depressed. The images were in color and were presented within a 6.7° by

6.6° neutral colored rectangle, which was framed by a black background. The visual stimuli were presented in the center of the screen. Participants made button-press responses on the number pad of the keyboard; they were instructed to press 1 when the index finger was depressed in the image and 2 when the middle finger was depressed. All other aspects of the display and testing conditions were the same.

Procedure

The voice-recognition testing was conducted in the same manner as Experiment 1. The instructions were the same except for the necessary modifications to reflect the appropriate responses to the new stimuli. Everything else including the timing of events, block order, and trial sequence was identical to the previous experiment.

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (2% of the remaining experimental trials) were also eliminated. Overall accuracy was 98%.

Reaction times from the single task trials only were examined for the AV and VM tasks (white bars, Figure 2). For the AV task, participants' mean RTs were 338 ms and 479 ms for the VM task. RTs for both tasks were very similar to Experiment 3 from Halvorson et al. (2012). RTs were 19 ms faster in this experiment for the AV task and 4 ms slower for the VM task, $ts<1$.

The data from each task were submitted to a one-way ANOVA with block-type (single, OR, and AND) as the sole factor. For the AV task, there was a significant main effect of block-type, *F*(2,38) = 23.15, *MSE* = 545.86, *p*<.001. As illustrated in Figure 2, participants were 33 ms slower in the OR blocks (368 ms) than in the single-task blocks (335 ms), *t*(19)=6.82, *p*<.001, indicating a mixing cost. The difference between RTs in the OR blocks (368 ms) and AND blocks (374 ms) was not significant, *t*(19)=1.80, *p*=.10 for the AV task. Thus, according to this measure, which holds constant the S-R mappings that must be maintained in working memory, no significant dual-task costs were observed.

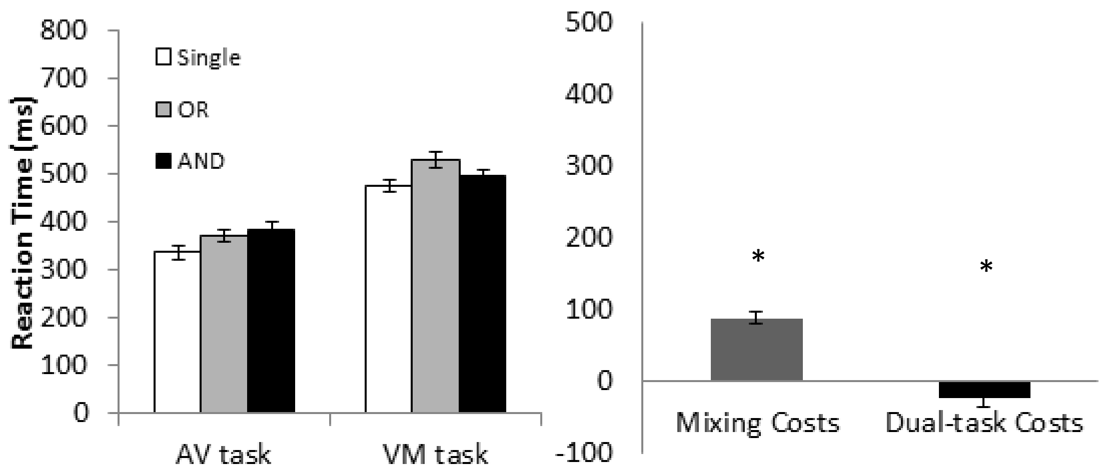


Figure 2. Findings from Experiment 2.
Left panel: mean RTs for the each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

A second measure of dual-task performance can be obtained by comparing RTs from AND blocks with RTs from pure single-task blocks. Single-task blocks were 39 ms faster than AND blocks, *t*(19) = 6.39, *p*<.001. Thus, this measure, which holds uncertainty constant but varies the number of tasks that need to be prepared, indicates a small dual-task cost is observed with these stimuli. The overall pattern of results is very similar to Experiment 3 from Halvorson et al. (2012).

A similar pattern was observed for the VM task. The one-way ANOVA with block-type was significant, $F(2,38) = 13.47$, $MSE = 108.77$, $p<.001$. Once again, the mixing costs were significant; participants were 52 ms slower to respond to a single stimulus when they had to keep multiple task sets active and trial type uncertainty was high compared to pure, single-task blocks, $t(19) = 11.67$, $p<.001$. When RTs from the OR blocks are used as a baseline for measuring dual-task costs, the opposite pattern was observed. RTs were significantly shorter in the AND blocks (487 ms) than in the OR blocks (521 ms), $t(19) = 2.98$, $p<.05$. Thus, instead of showing evidence of dual-task costs, the data suggest that uncertainty about which task would be required to be performed slowed performance more than the requirement to make two concurrent responses. The alternative measure of dual-task costs, the comparison of RTs from the AND trials to RTs from the single-task trials, was not significant, $t(19) = 1.50$, $p=.16$. This suggests that participants were not significantly slowed when required to make two responses.

Overall RTs were also calculated for each task, averaged across block type. For the AV task, mean RTs were 366 ms, and 502 ms for the VM task. Compared to the AV task from Experiment 1 (537 ms), RTs in this experiment were 171 ms faster, $t(59)=11.31$, $p<.001$. Compared to the VM task from Experiment 2 (502 ms), RTs in this experiment were 90 ms faster overall, $t(59)=5.12$, $p<.001$. Thus, the IM-compatible task pairing not only changes the between block comparisons, but also reduces the amount of time it takes to perform each task even though both experiments use the exact same responses.

Mixing and Dual-task Costs

As in Experiment 1, the sum of the mixing and dual-task costs was calculated across tasks (Figure 2, right panel). There was a significant 89 ms mixing cost overall, $t(19)=11.28$, $p<.001$. This is consistent with the findings from Halvorson et al., (2012). Maintaining both task sets slows responses even when participants are only making one response on a given trial. Chapter 7 will contain fine-grained analyses that will illuminate the source or sources of these costs by looking at differences in RT based on trial by trial differences. For the moment, it is very important to note that the presence of mixing costs strongly suggests that even though the relationship between the stimuli and the responses is highly compatible, simply maintaining the S-R pairs in working memory places a demand on the system. This reinforces the use of multiple types of single-task trials and calculating the mixing and dual-task separately.

The sum of the dual-task costs was marginally significant, -24, $t(19)=2.09$, $p=.051$. However, the cost was negative which means that participants were actually slower in the OR blocks than the AND blocks. Thus, there is little evidence that making performance suffers when making two responses compared to one response when both tasks are IM-compatible. This represents a dramatic departure from the costs observed with very similar tasks in Experiment 1.

Accuracy

Accuracy for the AV task was 97% and 98% for the VM task. A separate ANOVA with block-type (single task, OR, AND) as a within-subject factor was conducted for each task. The main effect of block-type was not significant for the AV task, $F<1$, or for the VM task, $F(2,38) = 2.09$, $MSE = .000$, $p=.137$. This pattern of results shows no real differences in accuracy across block types, which is consistent with what was observed in the RT data.

Summary

The results from this experiment replicated the findings from Experiment 3 in Halvorson et al. (2012) and suggest that when two IM-compatible tasks are used, participants can make two responses as efficiently as one response. Although these results replicate previous findings, the absence of dual-task costs is still unusual compared to costs typically reported. Among the few studies that have reported minimal dual-task interference, most have used nearly identical task pairings. Previously, researchers have made small changes to the overall task structure in order to find the optimal testing conditions for observing dual-task performance. The experiments reported here take a different approach; all of task pairings examined here use the exact same block types, methods, instructions, and timing of events. The aim of these studies is to manipulate aspects of the tasks in an effort to identify factors of the task pairing that result in dramatic changes in the magnitude of the dual-task costs. As discussed previously, dual-task interference depends critically on the task pairing. It is not possible to predict, based on costs observed for a single task used in a previous study, whether the costs associated with that task will be the same when paired with a different task. This is the case even when the input and output modalities of the other task are kept constant. As such, there is an almost infinite possibility for task pairings that could be used for testing dual-task interference – *even* if the input and output modalities remain the same.

For this reason, all of the experiments reported here will use the exact same responses. This eliminates the possibility that the magnitude of the dual-task costs will be affected by differences in the difficulty of executing the motor responses. Instead, the stimuli that the responses are paired with and in some cases the S-R mappings will be systematically varied across experiments.

Given the similarity between the two task pairings used in Experiments 1 and 2, the dramatic difference in the magnitude of the dual-task costs is surprising. Only the stimuli, and necessarily the mappings, were varied between experiments. The next section contains summaries of the four possible hypotheses that will be tested in the experiments reported here. These experiments aim to examine the factors that may have led to the dramatic difference in costs between Experiments 1 and 2, as well as task pairings in which only one of the tasks is IM-compatible and the other is arbitrary.

Four possible hypotheses

Following the logic of Greenwald's original formulation of IM theory, one IM-compatible task should have been able to be performed without engaging central response selection mechanisms, thereby allowing the second task to be performed as efficiently under dual-task situations as single task. However, Halvorson et al. (2012) (see also Lien et al., 2002) showed that one IM-compatible task and one task with an arbitrary S-R mapping resulted in large dual-task costs. As such, IM theory cannot accommodate the existing patter of results. The following section describes four alternative hypotheses that can all account for findings of highly efficient dual-task performance when both tasks met the criteria for IM-compatibility as well as dramatically larger dual-task costs with just one IM-compatible task. Critically, the four hypotheses make different predictions about the factors of the task pairing that produce dual-task interference.

Automatic activation hypothesis

The first hypothesis is the *automatic activation* hypothesis. This hypothesis suggests that the minimal dual-task costs observed with two IM-compatible tasks is the result of an unusually high amount of compatibility between the stimuli and responses for each task. According to this account, the similarity between the stimuli and responses within each task results in a significant increase in the amount of dimensional overlap for the S-R pairs. Dimensional overlap is a term first used by Kornblum et al. (1990) to describe the relationship between sets of stimuli and responses; the greater the number of distinct, but correlated, ways in which the stimuli and responses are similar, the more dimensional overlap there is for the S-R pairs. When S-R pairs contain a sufficiently high level of dimensional overlap, the amount of time it takes to select the correct response is dramatically reduced because encoding the stimulus results in automatic activation of the response. As the strength of the automatic activation increases, response selection becomes increasingly more efficient. If the automatic activation reaches a critical level, it may be that a direct link arises between a specific stimulus and its associated response that does not engage traditional response selection mechanisms to the same extent as less compatible S-R mappings.

Similar accounts have been used to explain findings of reduced impairment following significant amounts of practice (see e.g. Hazeltine et al., 2006). Presumably, when participants become highly practiced with a particular task pairing, the stimuli and response for each task become so strongly associated that a direct route is established between a given stimulus and the correct response. In this way, the IM-compatible tasks used in Halvorson et al. (2012) may have been uniquely suited to avoid dual-task interference. Even though participants did not spend a significant amount of time practicing the particular S-R pairings as part of the experiment, IM-compatible tasks could be benefitting from their similarity to common, everyday tasks. Participants' experiences saying words in response to words, as in everyday conversation, and typing on keyboards may have essentially served as extensive practice.

Thus, the automatic activation predicts minimal dual-task costs when the similarity between the stimuli and responses for both tasks is sufficient to automatically activate the correct response. Although automatic activation is very similar to the relationship between the stimuli and responses described in Greenwald's IM theory, there are a couple of important differences. First, the automatic activation does not include some of the fundamental changes to traditional theories of response selection proposed in IM theory. Unlike IM theory, the automatic activation hypothesis does not require that participants select the environmental outcome of the desired response rather than the response itself. This makes the automatic activation hypothesis more amenable with traditional theories of response selection, including many bottleneck theories. Secondly, whether or not responses can be automatically activated for one task could depend on the relationship between the S-R pairs for the other task. If the second task is an arbitrary task in which the responses are not automatically activated, it could cause the system to adopt a "greedy resource" theory in which the task requiring more resources is processed first. This may reduce the efficiency of the automatic activation from the other task, and require even the highly compatible S-R pairs to be processed more slowly. This could allow for predictions of the magnitude of the dual-task costs to depend on the relationship between the two tasks in a way that IM theory cannot and explain the findings of significant dual-task costs with only one IM-compatible task.

To test this hypothesis, the experiments in Chapter 3 will use the exact same stimuli and responses, but will use different S-R mappings thereby eliminating the extreme levels of compatibility (and in fact adding a significant amount of interference) between the individual S-R pairs.

Task coherence hypothesis:

In addition to the fact that the IM-compatible tasks used in Halvorson et al., (2012) have a unique relationship between each stimulus and the correct response, there is also a large amount of overlap at the conceptual level to the extent that participants could be grouping all four S-R pairs into a single task. Because the tasks were imitative in nature, responses for both tasks could be selected by using one common rule: "do what you perceive." Thus, when the task pairing consisted of two IM-compatible tasks, only one translation rule was required to select both responses. It is possible that in the AND blocks, even though participants were actually executing two responses, the relationship between the tasks essentially allowed participants to treat the two tasks as a single task. This would also explain why the magnitude of the costs was dramatically larger when only one IM task was used. In those experiments, participants could not use a single rule to combine the two tasks.

To test whether a high degree of task coherence leads to minimal dual-task costs, I changed the rule associated with one or both of the (previously) IM-compatible tasks *without* changing anything about the actual stimuli and responses. Instead, I instructed participants to “do the opposite” of whatever action is depicted or word is spoken. By manipulating the rule associated with each task, I can examine whether dual-task costs are dramatically reduced when both tasks share a single rule even when they clearly do *not* meet the criteria for IM-compatibility.

Task set confusion hypothesis:

This hypothesis suggests that two IM tasks lead to minimal dual-task interference not by virtue of the overlap at the conceptual level, but instead because of the extent to which the two tasks can be kept separate. This hypothesis predicts that dual-task interference arises because of task set confusion during the binding process; choosing the correct response for a given stimulus will be more difficult in a dual-task when there is overlap between the S-R pairs such that the stimulus for one task activates information related to a possible response for the other task. In the IM tasks, the stimuli for the VM task (i.e. images of hands) are likely very strongly associated with making manual responses, and importantly, *not* associated with the vocal production of the words “cat” and “dog.” Similarly, hearing the words “cat” and “dog,” is not likely to activate button press responses with the index or middle finger. The experiments in Chapter 4 will use stimuli that maintain this separability between the two tasks, but do not have the direct relationship between the individual S-R mappings as in the IM tasks or share a common rule as in the IM and “Opposite” tasks.

Central code crosstalk hypothesis

The last hypothesis is a novel hypothesis I have proposed called the *central code crosstalk* hypothesis. This hypothesis combines multiple-resource theories (e.g., Wickens, 1984) and crosstalk theories (Navon & Miller, 1987). According to resource theory, dual-task interference arises when tasks require the use of resources from the same, capacity-limited pools. Wickens's (1984) code-compatibility hypothesis suggests that dual-task interference depends critically on the type of central code required to bind the stimulus and response. When S-R pairs are formed, the binding process requires participants to use central codes (C) that connect the stimulus with the response. For example, in the AV task, the tasks consist of *three* parts: the auditory stimulus, a central verbal code, and the vocal response; its S-C-R combination. He claims that similarity between these central codes causes competition for a common resource and is the primary source of interference between tasks.

Crosstalk accounts suggest that dual-task costs arise whenever some component of one task affects a variable that is relevant for performance on the other task (Navon & Miller, 1987). The amount of crosstalk present is not the same as the competition for limited resources; rather, crosstalk refers to whether an element of one task incorrectly activates some element of the opposite task. Navon and Miller (1987) showed that crosstalk affects performance by causing interference when the stimuli for one of the tasks were related in a conceptual or semantic way to the stimuli for the other task.

The *central code crosstalk hypothesis* adopts the term central code from Wickens's (1983) multiple-resource theory and applies it to a crosstalk account; this hypothesis suggests that crosstalk must be eliminated between all three components of the task: the stimuli, central codes and responses, in order to minimize dual-task interference. This hypothesis predicts that when two tasks use distinct input and output modalities and one task requires a spatial code (e.g. the VM task) and the other task requires a verbal code (e.g. the AV task), dual-task costs will be minimal. This hypothesis will be tested by using two tasks that use distinct input and output modalities, but do not use images of hands for the VM task. Instead, the VM task will be a spatial task that requires a manual keypress in response to the corresponding spatial location of a target paired with the AV shadowing task. Follow-up experiments will test the boundary conditions and novel predications for dual-task performance of this hypothesis by using an AV task that is not a verbal shadowing task (but still uses a verbal central code) and non-standard input and output modality pairings (while keeping the central codes distinct).

The aim of Chapter 6 is to investigate the level at which dual-task interference arises. More specifically, although it has been shown that dual-task costs depend critically on the task pairings, the level at which interference between the task pairings results in dual-task interference has not been established. That is, are dual-task costs *dynamically* determined on a given trial, or does crosstalk between the S-R pairs for each task affect performance even if the particular S-R pairs on the current trial do not interfere with each other? To address this question, I conducted an experiment in which one of the S-R pairs for each task was selected from an experiment in which no dual-task costs were observed (e.g. an image of a hand with the index finger depressed mapped to an index finger keypress and the “cat” – “cat” mapping from the verbal shadowing task) and the other S-R pair for each task had an arbitrary relationship which resulted in large dual-task costs in a different experimental context. By comparing the overall magnitude of the dual-task costs with the amount of interference on a trial by trial basis, this experiment will examine whether dual-task costs are determined by the amount of crosstalk on a given trial or whether the presence any crosstalk between the two task sets will result in dual-task costs (even if there is no crosstalk on the current trial).

These four hypotheses make vastly different claims about the source or sources of dual-task interference. The following chapters will test these claims by manipulating aspects of the task pairings.

CHAPTER III

CHANGING THE MAPPINGS

Despite the limited number of studies reporting little to no dual-task costs when executing two responses compared to a single response, Halvorson et al. (2012) and Experiment 2 showed that two tasks can be performed as efficiently as single task trials when the number of stimulus-response alternatives was held constant. As discussed previously, these experiments used tasks that closely adhere to the definition of IM-compatibility first proposed by Greenwald and Shulman (1973). IM-compatibility is a term used to refer to a unique class of tasks in which the S-R pairs are highly compatible in such a way that "the stimulus resembles sensory feedback from the response" (Greenwald & Shulman, 1973, p. 70). This additional criterion sets IM tasks apart from compatible S-R pairs in which "natural or highly learned associations are involved" (Greenwald & Shulman, 1973, p. 70). However, the evidence from Experiments 5 and 6 in Halvorson et al. (2012) makes Greenwald's original claims about IM-compatible tasks bypassing response selection untenable. In spite of such theoretical claims offering little explanatory value, I will continue to use the label IM-compatible to refer to the AV and VM tasks in which the stimuli highly resemble some sensory aspect of the response to distinguish them from other compatible S-R pairs.

Automatic Activation Hypothesis

The first aim of this chapter is to test the *automatic activation* hypothesis proposed in Chapter 2. The automatic activation hypothesis explains the minimal dual-task costs with two IM tasks because of the extreme compatibility within the S-R mappings for each task. In these tasks, the high level of compatibility for each of the S-R pairs increases the efficiency of the activation of the correct response code to the extent that the stimulus automatically activates the correct response. This automatic activation could lead to the dramatically reduced dual-task interference observed in Halvorson et al. (2012). Although the automatic activation hypothesis may run into the same difficulty as the IM theory in explaining the large costs when only one task is IM-compatible, this hypothesis is being considered for two reasons. The first is that there are some ways in which automatic activation might be required for both tasks in order to alleviate dual-task costs. The second is that this is perhaps the most common explanation for reductions in dual-task interference (see e.g. Hazeltine et al., 2006). These possibilities will be discussed in the following paragraphs.

In a series of experiments, Lien et al. (2002) showed that the IM tasks used in Greenwald and Shulman's (1973) study resulted in significantly faster overall RTs compared to compatible S-R pairs, and a dramatic reduction in the standard PRP effect. However, since all four experiments showed evidence of a significant (albeit reduced) PRP effect, the authors took issue with the Greenwald's conclusion that these tasks bypassed the bottleneck stage. Instead, they suggested that IM tasks are compatible in multiple ways that proves advantageous for dual-task performance. It has been well established that compatible S-R mappings allow responses to be selected highly efficiently and reduce overall RTs (see e.g., Smith, 1967). Some theories of response selection suggest that compatible mappings increase the amount of dimensional overlap between the stimulus and response sets, reducing the time it takes to choose the correct response (see e.g. Hommel, 1998; Kornblu, Hasbroucq, & Osman, 1990).

Kornblum et al.'s (1990) model uses the term dimensional overlap to refer to the extent to which the stimuli and response sets share attributes or features. This theory allows for multiple sources of similarity between the stimulus and response sets that can lead to dimensional overlap; S-R pairs can be conceptually similar, as well as physically, or perceptually, similar. Lien et al. (2002) pointed out Greenwald and Shulman's (1973) IM tasks contained a higher degree of dimensional overlap than the S-R compatible tasks. For example, in the VM task alone, there were at least two spatial cues correlated with the correct response. There was conceptual similarity because the direction the arrow was pointing indicated the direction of the movement required for the correct response. There was also a high degree of perceptual similarity because of the spatial compatibility between the physical location of the stimuli on the screen and the physical location of the responses: the left- and right-pointing arrows appeared slightly offset from center on the left and right sides of the screen respectively. Similarly, in the AV shadowing task, the conceptual similarity between the stimuli and the responses was extremely high (they were the same letter), as was the physical similarity (hearing and producing the same spoken letter results in highly similar perceptual experiences).

The VM task using images of hands also has a high level of dimensional overlap. There is a large degree of conceptual similarity between the stimuli and response because the images with either the index of middle finger depressed required a response with the index or middle finger of the participant. One could also argue that there is perceptual similarity between viewing an image of a hand with an index finger depressed and the perceptual feedback associated with the production of a keypress with the index finger. Brass, Bekkering and Prinz (2001) argued that "the visual response image is one of the major parts of sensory action feedback…[and] observing an action activates the response image of the corresponding response" (p. 5). Although the stimuli in this task are static and participants did not observe the preceding action, there is substantial correspondence between viewing an image of a hand in a position that corresponds with the participants' view of their hands following the action. Taken together, in addition to the fact that the index and middle finger responses have a left- and rightmost relationship in common with the stimuli, the relationship between the stimulus and response sets in the IM-compatible tasks likely resulted in an extremely high degree of dimensional overlap.

The strongest evidence against Greenwald and Shulman's (1973) claim that IM tasks bypass response selection comes from experiments in which one of the tasks is IM compatible and the other is S-R compatible (e.g. Greenwald & Shulman, 1973, Experiments 1 and 2; Lien et al., 2002, Experiments 1 and 2; Halvorson et al., 2012, Experiments 4 and 5). As stated previously, if IM tasks bypass response selection, then IM theory would predict no dual-task costs when only one task is IM compatible even if the other has an arbitrary relationship. However, all the findings to date, including Greenwald and Shulman's (1973) original experiments, show substantial increases in the magnitude of the dual-task interference in these cases.

Findings of increased dual-task interference when just one of the tasks is S-R compatible or arbitrary compared to situations with two IM-compatible tasks can be accounted for by dimensional overlap models of response selection (Hommel, 1998; Kornblum et al., 1990). These theories break down the response selection process into at least two separable component parts: activation of the response code and intentional response selection (Lien et al., 2002, p. 406). Accordingly, dimensional overlap facilitates activation of the response code; extremely high levels of dimensional overlap, as in the IM-compatible tasks, can lead to automatic activation of the response code. However, these theories claim that all S-R tasks – including IM-compatible tasks – require the responses to be initiated regardless of the level of dimensional overlap. Thus, Lien et al., (2002) argue that the second stage of response selection, initiating the required movement, can only be performed for one task at a time and gives rise to the significant PRP effect observed in their studies.

In light of the evidence that the PRP paradigm and the simultaneous presentation paradigm show discrepant findings with the exact same tasks, it is possible that it is possible that the residual PRP effect observed in Lien et al. (2002) was not caused by interference during the intentional movement selection stage but was an artifact of the task structure. Thus, it is possible that two tasks with extremely high levels of dimensional overlap could automatically activate the correct response to the extent that initiating the required movement can occur simultaneously for two tasks when the right task structure and instructions are used. Moreover, the amount of time it takes to complete the second stage of response selection, intentional movement initiation, could be affected by the number of S-R pairs being maintained in working memory. By calculating dual-task costs based on single-task trials from the OR blocks the number of possible responses to choose from was kept constant in the single- and dual-task conditions, which could have made response initiation stage the same for both trial types.

Kornblum et al.'s (1990) claim that compatibility effects can lead to automatic activation of the response has been used to explain the dramatically reduced dual-task costs observed in practice studies. As suggested in Hazeltine et al. (2006), repeated exposure to the S-R pairs might increase the strength of the automatic activation of the responses to the extent that responses can be made based only on the automatic activation (perhaps eliminating the need for the second response selection stage altogether) thereby avoiding potential source of dual-task interference. Instead of belonging to a special category of tasks that bypass response selection, IM-compatible tasks could be tapping into a dearth of real-world experience that functions the same as several session of practice in the lab. In other words, when we are typing on a keyboard and we see our fingers depress keys, we are really “practicing” the VM task used in Halvorson et al. (2012) and Experiment 1. Likewise, daily conversations and communicating facilitates a similar type of “practice” with the AV shadowing task.

As such, the *automatic activation* hypothesis predicts minimal dual-task interference when both tasks are either highly practiced or contain a sufficient amount of dimensional overlap such that the stimulus automatically activates the correct response. In other words, Experiments 3-5 will test whether the costs are eliminated by virtue of the tasks’ high levels of compatibility. To test this account, in Experiments 3-5 the mappings for the S-R pairs will be manipulated while keeping the physical stimuli and responses identical.

There are two possible mappings for the S-R pairs: the IM mappings used in Experiment 1 and an opposite (OPP) mapping in which the stimulus the responses were assigned to the non-corresponding stimulus. In the OPP AV task, “dog” required the response “cat” and vice versa. Likewise for the OPP VM task, an image of a hand with a depressed index finger required a keypress with the middle finger (and vice versa). The mappings were manipulated for both tasks in a 2x2 between-subjects design in which tasks used IM mappings, both tasks used OPP mappings, or each task used a different mapping.

Experiment 3 is the OPP-OPP condition: the mappings were reversed for both tasks. In this experiment the S-R pairs for both tasks clearly no longer meet the criteria for IM-compatibility. More importantly, the reversed mappings dramatically reduce the amount of dimensional overlap for both tasks. Although there is still conceptual similarity between viewing an image of a hand and making a manual keypress, the correspondence between the finger depressed in the image and the finger required for making the correct response has been eliminated. Moreover, the left-right relationship between the stimulus and the response present in the IM task is no longer useful for selecting the correct response. Likewise, the AV task with opposite mappings retains some amount of conceptual similarity, but the physical correspondence between the stimulus and the correct response is greatly reduced. Thus, the automatic activation hypothesis predicts large dual-task interference for this experiment because the two tasks no longer have extremely high levels of dimensional overlap; the opposite mappings should not result in automatic activation of the correct response following the presentation of the stimulus.

If minimal dual-task costs are observed, it is possible that the real-world "practice" participants have likely accumulated making keypresses in response to visual input and saying words in response to words also facilitates performance in situations in which the S-R mappings are incompatible. Alternatively, it is possible that because the stimuli for the VM task are images of hands, manual responses are automatically activated by virtue of a direct route established not by practice but by virtue of the embodied nature of the stimuli. These issues will be taken up directly in subsequent experiments.

Experiments 4 and 5 will examine dual-task performance when one task uses the opposite mapping and the other task uses the imitate mapping. According to the automatic activation hypothesis, these task pairings should result in mid-range dual-task costs. Although the overall level of dimensional overlap has been reduced compared to situations two incompatible mappings, if one of the tasks depends heavily on central resources involved in selecting the right response, it could reduce the efficiency of the automatic activation for the other task, resulting in both tasks competing for limited central resources necessary for choosing the correct response. This competition will cause interference during dual-task trials and result in measurable increases in dual-task costs.

Task Coherence hypothesis

A unique feature of the IM-compatible tasks is that they essentially share the same "rule." In addition to the fact that the IM-compatible tasks used in Halvorson et al., (2012) have a highly compatible relationship between each stimulus and the correct response, there is also a large amount of overlap at the conceptual level to the extent that participants could be grouping all four S-R pairs into a single task. Because both tasks were imitative in nature, responses for both tasks could be selected by using one common rule: "do what you perceive." In the AV task, participants simply had to echo what they heard and in the VM task they had to mimic the movement depicted on the screen. Sharing a rule might allow two tasks to be treated as a single task with four S-R pairs as opposed to two tasks with two S-R pairs. If that is the case, participants would effectively be doing a single task in both the OR blocks (where one stimulus required participants to select a response from four possible S-R alternatives) and the AND blocks where two stimuli required two responses selected from the same four S-R alternatives. Thus, the *task coherence* hypothesis suggests that dual-task costs are avoided when participants can use the same "rule" to do both tasks thereby only engaging the central response selection mechanism once to correctly select both responses. This hypothesis also accounts for the large dual-task costs observed when only one of the tasks was IM-compatible because the two tasks required distinct translation rules which could not be reconciled into a single task.

The opposite 2x2, in which the instructions were changed such that participants were required to "do the opposite" for one or both of the tasks, will also directly test the task coherence hypothesis. According to the task coherence hypothesis, Experiment 3 (both tasks use the opposite rule) will result in a very similar pattern of results as the IM-IM experiment; specifically, minimal dual-task costs. However, this hypothesis predicts large dual-task costs when one task requires participants to do the opposite and the other requires them to mimic what they see or hear. In these cases (Experiments 4 and 5) the two translation rules prevents consolidation of the four S-R pairs into a single task and large differences in RT should be observed in the AND blocks compared to the OR blocks.

Changing the rule associated with the tasks is also a way of testing some of the claims made by EPIC, the computational model described in Chapter 1 that uses production rules to govern dual-task performance (Meyer & Keiras, 1997). Previously, I suggested that the imitate rule that applied to both tasks in the IM-IM case might have allowed the central processor to shift from lockout scheduling to interleaved scheduling without significant amounts of practice. This same prediction can be made for the OPP-OPP experiment. Even though participants may not be highly practiced making the "opposite" response (with respect to the give S-R pairs), the single rule makes scheduling highly efficient. However, both EPIC and the task coherence hypothesis predict that requiring participants to use two distinct rules, as in the OPP-IM and IM-OPP experiments will result in costs. According to EPIC, two rules should cause the system to revert to lockout (or serial) scheduling of the tasks if participants are in fact using the rules to choose the correct response.

Changing the mappings for the IM tasks by using the "opposite" rule serves the dual purpose of testing the task coherence hypothesis as well as reducing the compatibility within the S-R pairs such that the overall dimensional overlap will be reduced, allowing for simultaneous testing of the automatic activation hypothesis. Critically, these hypotheses make opposing predictions with regard to the magnitude of the dual-task costs in the OPP-OPP experiment. As such, the findings from the OPP 2x2 will eliminate at least one of the first two hypotheses.

Experiments 3-5: "Do the opposite"

These three experiments (in addition to Experiment 2) will test the automatic activation and task coherence hypotheses of dual-task interference. These two hypotheses make diametrically opposed predictions as to the magnitude of the dual-task costs for Experiment 3. Methods, results and inferences for the first experiment (IM-IM, top left corner, Figure 3) were reported in the previous chapter; Experiment 2 represents the first cell of the 2x2 design.

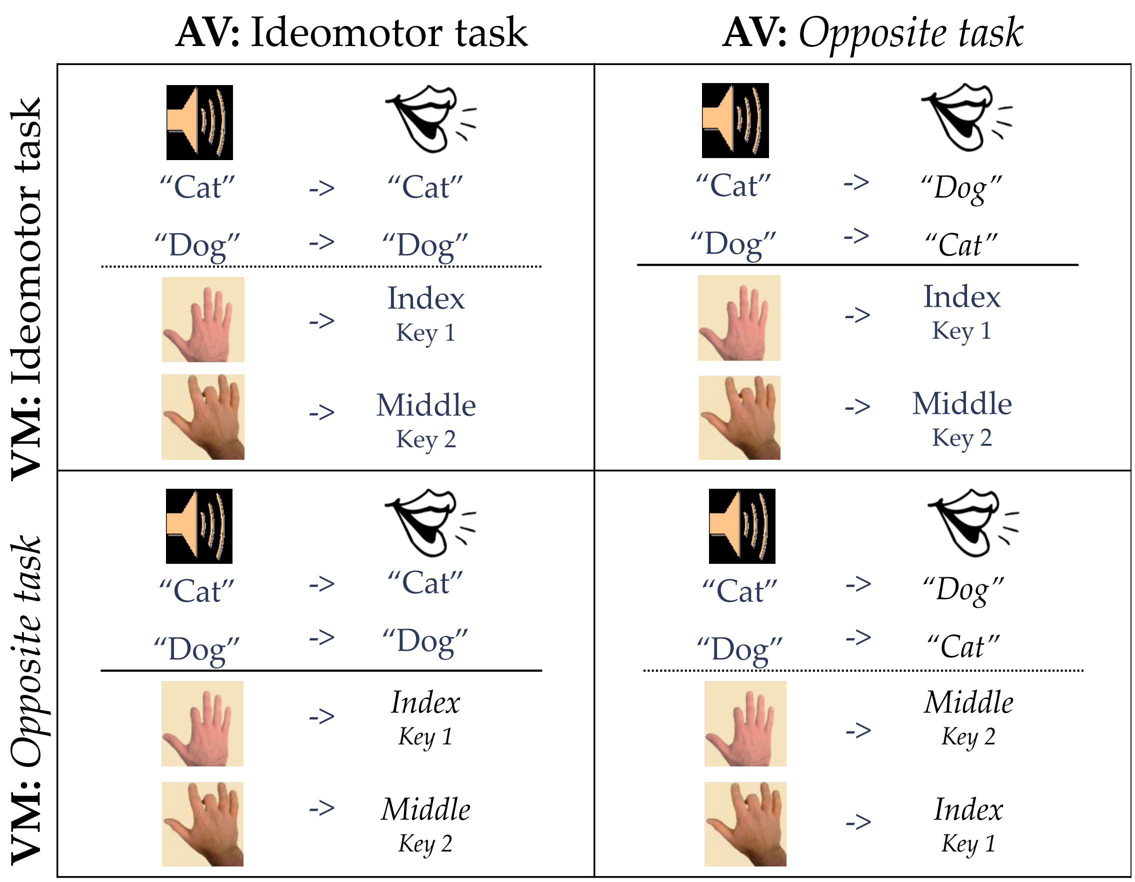


Figure 3. A diagram of the opposite 2x2 design

Experiment 3: OPP-OPP

In the OPP-OPP experiment (bottom right corner, Figure 3), participants were instructed to "do the opposite" for both tasks. In the AV task if they heard "cat", they were instructed to say "dog" and vice versa. The same instructions were given for the VM task. Other than the rule associated with the task, the stimuli, timing of events, and responses were identical to Experiment 1.

Experiment 4: OPP-IM

Experiment 4 is the OPP AV, IM VM (OPP IM) experiment (top right corner, Figure 3). Participants were instructed to “do the opposite” for the AV task and do “repeat what you see” for the VM task. In the AV task if they heard “cat”, they were instructed to say “dog” and vice versa. In the VM task, they were instructed to make a response based on the depressed finger in the image. Other than the rule associated with the task, the stimuli, timing of events, and responses were identical to Experiment 1.

Experiment 5: IM-OPP

Experiment 5 is the IM AV, OPP VM (IM-OPP) experiment (bottom left corner, Figure 3). Participants were instructed to “repeat what you hear” for the AV task. In the VM task, they were instructed to “do the opposite”. So, if middle finger was depressed in the image on the screen, they were instructed to press the 1 key, and if the index finger was depressed they were instructed to press the 2 key. Other than the rule associated with the task, the stimuli, timing of events, and responses were identical to Experiment 1.

Participants

Twenty undergraduates from the University of Iowa (49 female, ages 19 – 25) were recruited to take part in all four experiments for a total of eighty subjects. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Results and Discussion

Trials were eliminated from the analysis in the same manner as all previous experiments: the first of each block type, an incorrect response on either task, or when RTs were either too fast or too slow. Trials where RTs exceeded 1500 ms or were shorter than 150 ms were eliminated. Single-task RTs are shown for each block type for all four experiments in Figure 4.

Before discussing the pattern of mixing and dual-task costs it is worth noting that the mean RTs for single and dual-task blocks varies depending on the task pairing. For the OPP-OPP experiment, RTs averaged across all block types were 412 ms in the AV task, which was significantly slower than overall RTs from the AV task in the IM-IM experiment, $t(59)=3.30$, $p<.01$. The VM RTs (569 ms) were also significantly slower than the IM VM task, $t(59)=3.62$, $p<.001$. In addition to affecting RTs on single-task blocks, the “do the opposite” instructions slowed performance across block types for both tasks compared to the experiment in which participants simply had to repeat whatever they perceived.

According to the task coherence hypothesis, the OPP-IM experiment (top right corner, Figure 4) should have resulted in large dual-task costs because each task used a different rule. Interestingly, overall RTs in the AV task (383 ms) were not significantly different than in the IM-IM experiment, $t(59)=1.56$, $p=.12$. This suggests that participants were able to say the opposite word that they heard as efficiently as they were able to repeat the word that was presented. For the VM task, IM RTs (507 ms) paired with an OPP AV task were not significantly difference than IM RTs when paired with an IM AV task, $t<1$.

For the IM-OPP experiment (bottom left corner, Figure 4), overall RTs in the AV task (378 ms) were not significantly different from the IM-IM experiment, $t(59)=1.76$, $p=.09$.

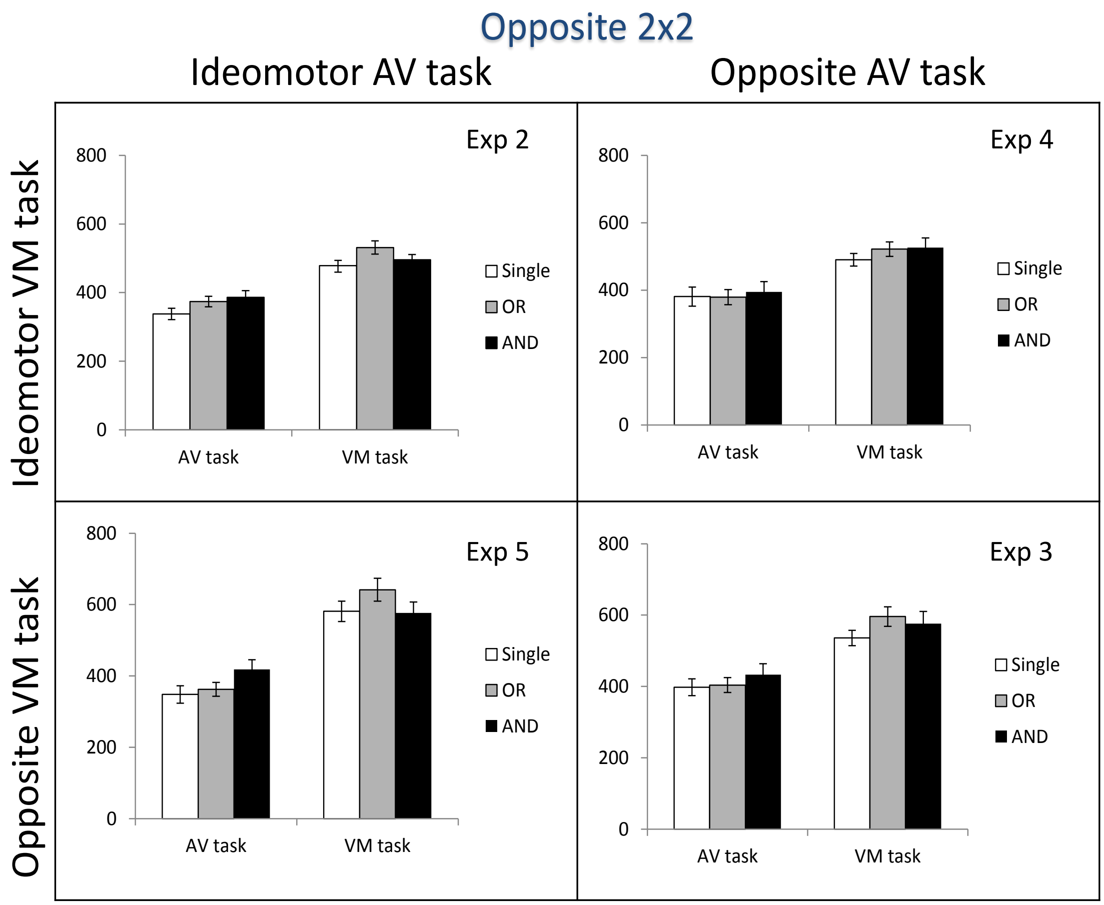


Figure 4. Findings from the opposite 2x2.
Error bars were calculated based
on the standard error of the mean.

Although the AV RTs were not different, overall RTs for the VM task (597 ms), were much slower than the IM VM task in the IM-IM experiment, $t(59)=6.98$, $p<.001$. These results suggest that the Opposite instructions significantly affected performance in the VM task no matter what AV task was paired with it and also slowed the AV task when both tasks required the opposite rule. Once again these findings stress the importance of the task pairings in evaluating dual-task costs. Presumably, changing the mappings for the S-R pairs should only affect the duration of the response selection stage.

Since these exact same stimuli and responses were used in all four experiments, the amount of time necessary to encode the stimulus and execute the response should be constant, allowing for critical comparisons of the magnitude of the mixing and dual-task costs across experiments.

Mixing and Dual-task Costs

Figure 5 shows that despite these differences in overall RT the pattern of results for the between block comparisons is strikingly similar across all four experiments. This is very surprising given the increased difficulty of the incompatible mappings. As reported earlier, the mixing costs were significant in Experiment 2 (IM-IM) but there was no evidence of dual-task costs. An identical pattern was observed in Experiment 3. For the OPP-OPP experiment (bottom right corner, Figure 5) the sum of the mixing costs was 66 ms, $t(19)=3.82$, $p<.01$, and the sum of the dual-task costs was a non-significant 5 ms, $t<1$. These results do not support the predictions of the automatic activation hypothesis. The incompatible mappings should have decreased the amount of dimensional overlap present in the S-R pairs, reducing the strength of the automatic activation and increasing the amount of conflict on dual-task trials. The lack of dual-task interference does, however, support the task coherence hypothesis. Even though the opposite rule slowed down the overall time required to make a response, there was no extra cost associated with making two responses compared to one when the number of S-R alternatives was held constant.

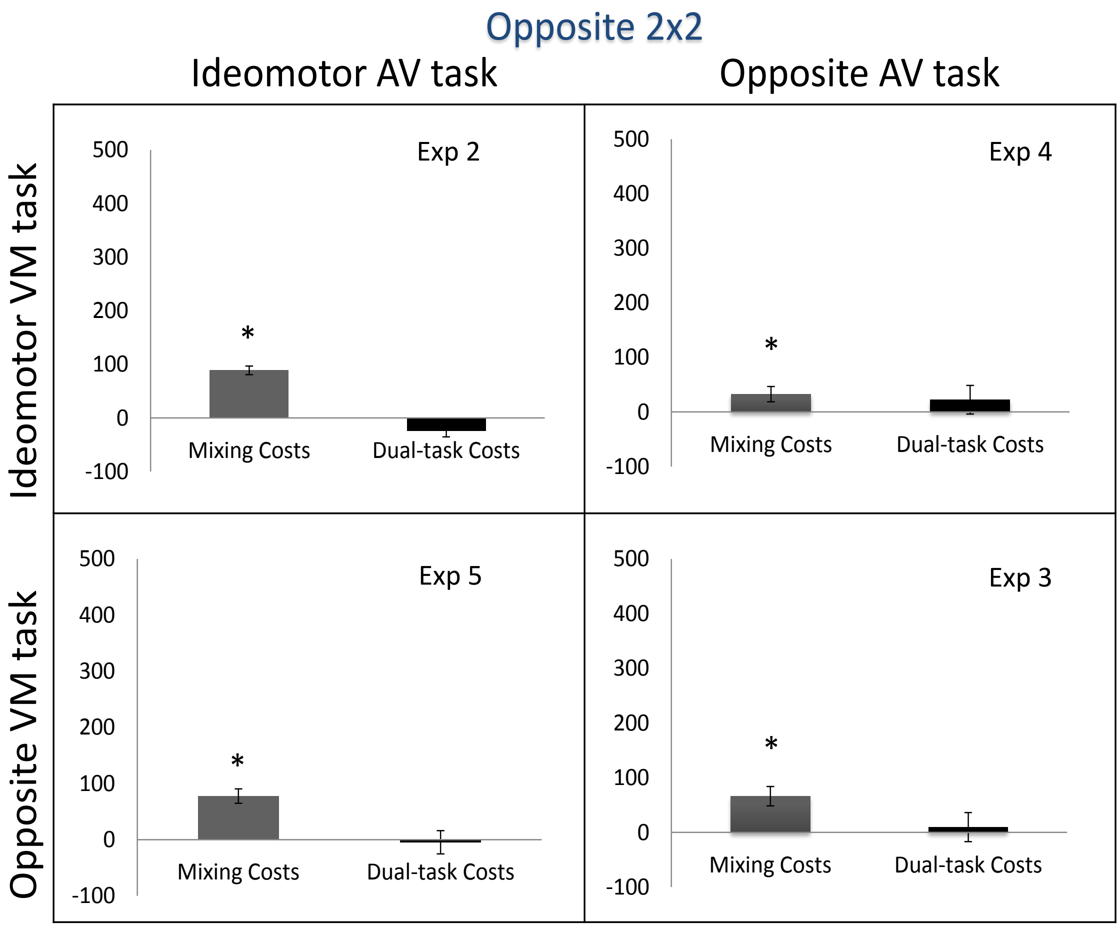


Figure 5. Sum of the mixing and dual-task costs for the opposite 2x2.

Surprisingly, the same pattern of results was observed in the remaining two experiments. For the OPP-IM experiment (top right corner, Figure 5), the mixing costs were significant, $t(19)=6.19$, $p<.001$, but the dual-task costs were not, $t<1$. Likewise for the IM-OPP experiment (bottom left corner, Figure 5), the mixing costs were significant, $t(19)=2.41$, $p<.05$, but the dual-task costs were not, $t<1$. Both hypotheses predicted either mid-range or large dual-task interference when a different mapping, or rule, was used for each task. The similarity in the magnitude of the mixing and dual-task costs compared to the IM-IM experiment is remarkable. Neither the reduction in dimensional overlap for one of the tasks nor the two distinct rules necessary for choosing the right response changed the magnitude of dual-task costs compared to Experiments 2 and 3. As such, neither of the first two hypotheses can account for the pattern of results from this 2x2.

Summary

No significant dual-task costs were observed for any of the experiments in the OPP 2x2. Surprisingly, changing one or both of the mappings to “do the opposite” did not affect the magnitude of the between block comparisons. Importantly, this 2x2 is a powerful demonstration of very efficient dual-task performance with two tasks that clearly do not meet the definition of IM-compatibility and represent a significant departure from tasks that have previously shown minimal dual-task interference (see Table 2). However, these results do not support either of the first two hypotheses. It does not appear that cases of minimal dual-task interference are the result of S-R mappings that are extremely compatible or participants’ conceptualization of all four S-R pairs as belonging to a single task.

Before delving into the factors that may have resulted in minimal dual-task interference, it is important to discuss the robust mixing costs observed regardless of the mean overall RTs or whether the mappings were compatible. Response selection includes both maintaining the information required to carry out each task successfully and selecting the appropriate action necessary to execute both responses. In the example of driving and talking on a cell phone, these costs are more or less equivalent to things like knowing traffic laws and the content of the conversation, and coordinating the foot and hand positions required to operate the automobile and the mouth and throat positions necessary for speaking, respectively. The consistent pattern of significant mixing costs makes it apparent that maintaining both S-R pairs in working memory increases cognitive load which has a marked effect on RT even when only one stimulus is presented and a single response is required on each trial. As such, previous measures of dual-task costs that conflated these two components may have over-estimated the interference involved in executing a second response. Fine-grained analyses reported in Chapter 7 will use trial by trial analyses to investigate the source or sources of the mixing costs.

When the cognitive load associated with maintaining both task sets is kept constant, performance in dual-task situations appears to be unimpaired regardless of the amount of compatibility present between the S-R pairs or whether participants were given one or two rules for the task pairing. One possibility is that instead of using the opposite rule for the VM task, participants were responding to the most visually salient aspect of the image (the finger that was *not* depressed) which was spatially compatible with the correct response. If this spatial compatibility created levels of dimensional overlap equal to that of the IM-compatible task, it is possible that the "opposite" manipulation did not affect the extent to which responses were automatically activated.

In order to explain the findings from Experiments 4 and 5, however, the opposite word pairings in the AV task must also automatically activate the correct response. However, this seems untenable because one stimulus cannot automatically activate both responses. It is possible that a significant amount of dimensional overlap in just one of the tasks is sufficient to minimize dual-task interference. Because the measure of dual-task costs used here keeps the cognitive load constant between single and dual-task conditions, this is a viable explanation. This possibility will be tested directly in Experiment 6, in which the same OPP AV task is paired with a new OPP VM task. In this OPP VM task, the opposite mapping is applied to images of hands with either the first or third finger depressed, requiring a keypress with the ring or index finger, respectively. These stimuli do not contain the spatial compatibility present in the previous OPP VM task. As such, neither of the tasks have a significant amount of dimensional overlap. Small dual-task costs in this experiment would be very difficult to reconcile with the automatic activation hypothesis.

Experiment 6: Testing the opposite rule

In this experiment the hand stimuli were different from those used in the OPP-OPP experiment; the AV task, the timing of events, and responses were identical to those used in Experiment 3.

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 25) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

Stimuli were presented on a PC computer using the exact same apparatus as the previous experiments and the stimuli for the AV task were identical to those used in Experiment 3. The visual stimuli were images of hands making the appropriate key press, although the keypad was not visible in the image. The images used were digital photographs taken of a right hand with either the index or ring finger depressed (see Figure 6). The images were in color and were presented within a 6.7° by 6.6° neutral colored rectangle, which was framed by a black background. The visual stimuli were presented in the center of the screen. Participants made button-press responses on the number pad of the keyboard; they were instructed to press 1 when the index finger was depressed in the image and 3 when the ring finger was depressed. The visual stimuli were presented on a 19” color LCD monitor that was located approximately 57 cm from the participant.

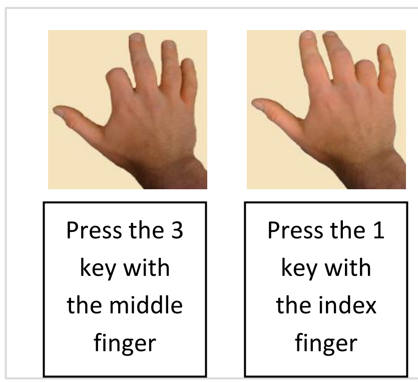


Figure 6. Stimuli and responses for the OPP VM task with first and third fingers

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (6% of the remaining experimental trials) were also eliminated. Overall accuracy was 96%. Reaction times from the single task trials only were examined for the AV and VM tasks (white bars, Figure 7). For the AV task, participants’ mean RTs were 415 ms and

581 ms for the VM task. Compared to Experiment 3, RTs were 3 ms slower in the AV task and 12 ms slower in the VM task, *ts*<1. The data from each task were submitted to separate one-way ANOVAs with block-type (single, OR, and AND) as the sole factor. For the AV task, there was no significant main effect of block-type, $F(2,38) = 2.34$, $MSE = 2054.02$, $p=.11$.

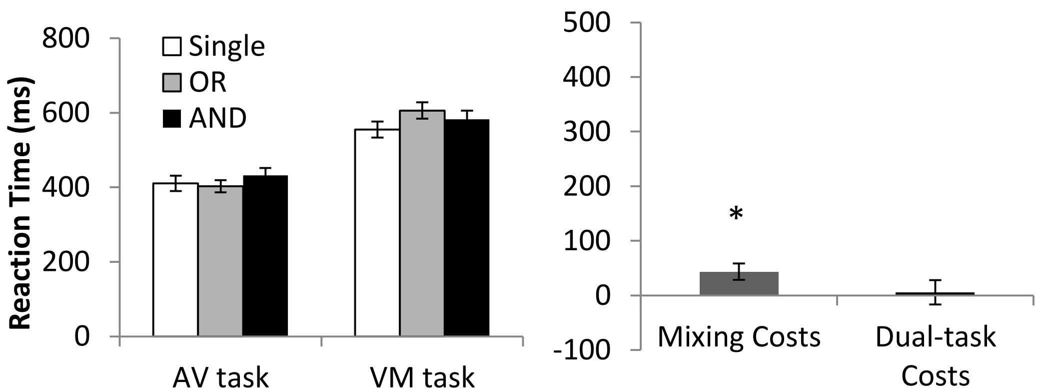


Figure 7. Findings from Experiment 6.
Left panel: Average RTs for each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

For the AV task alone, RTs were not significantly different in OR blocks (403 ms) compared to the single-task blocks (411 ms), $t<1$; RTs from AND blocks (432 ms) were marginally different from OR blocks, $t=1.95$, $p=.07$. A slightly different pattern was observed for the VM task; the main effect of block-type was significant, $F(2,38) = 11.06$, $MSE = 1193.41$, $p<.001$. For the VM task alone, the mixing costs were significant; participants were 51 ms slower when responding to a single stimulus when they had to keep multiple task sets active and trial type uncertainty was high compared to pure, single-task blocks, $t(19) = 4.96$, $p<.001$. When RTs from the OR blocks are used as a baseline for measuring dual-task costs, the opposite pattern was observed. RTs were significantly shorter in the AND blocks (582 ms) than in the OR blocks (606 ms), $t(19) = 1.67$, $p<.05$.

However, as in previous experiments, the sum of the costs for the two tasks provides a better measure of overall interference, given the possibility that participants may be strategically prioritizing one task over the other on dual-task trials (see Figure 7, left panel). Thus, when taken together, the significant mixing costs for the sum of the two tasks (43 ms, $t(19) = 2.96$, $p<.01$) suggest that uncertainty about which task would be required to be performed slowed performance more than the requirement to make two concurrent responses. When the number of S-R mappings that must be maintained in working memory was held constant, the sum of the dual-task costs for both tasks (6 ms) was not significant, $t<1$. This suggests that participants were not significantly slowed when required to make two responses. This pattern of results resembles the data from Experiment 3 in which the "opposite rule" was used for both tasks, but the index and middle fingers were depressed and 2 and 1 keypresses required respectively. This suggests that the lack of dual-task costs observed in the first OPP-OPP experiment (Experiment 3) cannot be solely attributed to the fact that there was spatial compatibility between the most visually salient finger in the image and the physical location of the correct response.

Accuracy

Accuracy for the AV task was 95% and 97% for the VM task. A separate ANOVA with block-type (single task, OR, AND) as a within-subject factor was conducted for each task. The main effect of block-type was marginally significant for the AV task, $F(2,38) = 2.85$, $MSE = .001$, $p=.070$, and the VM task, $F(2,38) = 3.14$, $MSE = .001$, $p=.055$. Follow-up t-tests for the AV task reveal significantly higher accuracy in OR blocks (96%) compared to single-task blocks (94%), $t(19) = 2.34$, $p<.05$, and the AND blocks (94%), $t(19) = 2.12$, $p<.05$, but no difference between the single-task and AND blocks, $t<1$. Given that RTs were the shortest in the OR blocks for the AV task, these data do not show evidence of a speed-accuracy tradeoff. For the VM task, accuracy in the single-task blocks (96%) was marginally different from the OR (98%), $t(19) = 2.06$, $p=.053$, but not the AND blocks (98%), $t(19) = 1.63$, $p=.11$. There was no difference between the OR and AND blocks, $t<1$. For this task, there may be some evidence of a speed-accuracy trade-off as the RTs were shortest and accuracy lowest for the single-task blocks. However, given the lack of significant main effects from the ANOVAs and the overall high accuracies, it is not likely that error played a large role in the main effects observed in the RT data.

In sum, the results from this experiment replicated the findings from Experiment 3 and show that when both tasks require participants to "do the opposite" of what they see or hear, participants can make two responses as efficiently as one. These results suggest that the findings from Experiment 3 could not have been solely due to participants using a strategy based on the spatial compatibility between the finger that was not depressed in the image and the location of the correct response.

General Conclusions

The first six experiments do not support the automatic activation or task coherence hypotheses proposed in Chapter 2. They also contribute to the growing body of evidence against Greenwald and Shulman's (1973) original claims about IM-compatible tasks bypassing response selection. A modified version of such a claim, the automatic activation hypothesis, also cannot account for the observed pattern of results. When the S-R mappings for each pair were reversed, the amount of dimensional overlap should have decreased significantly, resulting in large dual-task costs. Contrary to this prediction, although overall RTs were slowed when the opposite mappings were used, the pattern of mixing and dual-task costs was nearly identical to the condition in which the mappings were highly compatible. Although problematic for the automatic activation hypothesis, these results did conform to the prediction made by the task set coherence hypothesis. However, the remaining cells of the OPP 2x2 showed that even one each task used a separate rule, dual-task performance remained highly efficient, ruling out the task coherence account.

Experiment 6 directly tested the possibility that the OPP mappings were really just highly spatially compatible in an unintended way, and participants were able to exploit a direct route between the stimulus and the correct response based on the relationship between the location of the visually salient finger in the image and the location of the correct response. Even when the index and ring finger were used in the OPP VM task, there was no evidence of dual-task interference. Thus, the relationships between the individual stimuli and responses and the amount of coherence between the rules for the two tasks cannot fully predict the amount of dual-task interference for a given task pairing because the exact same responses were used for all the experiments. This is in direct conflict with the automatic activation hypothesis, because the same stimulus cannot automatically activate multiple responses; for example, the word "cat" cannot automatically activate the vocal responses “cat” and “dog.” Although the Opposite 2x2 manipulated both the relationships between the individual S-R pairs and the conceptual organization of the task pairing as belonging to one or two tasks, the relationship between the task sets, or the amount of correspondence between the S-R pairs, remained constant. In the following chapter, the relationships between the stimuli and responses will remain constant, as well as the conceptual relationship between the two tasks, and only the extent to which the task sets correspond will be manipulated.

CHAPTER IV

TASK SET CONFUSION HYPOTHESIS

The aim of this chapter is to test the *task set confusion* hypothesis. Chapter 3 showed that both tasks do not need to be IM-compatible to dramatically reduce dual-task costs. The incompatible mappings created by the “do the opposite” instructions tested both the automatic activation and the task coherence hypotheses. These hypotheses made different predications for the OPP-OPP experiment; according to the automatic activation hypothesis, the incompatible mappings should have decreased the dimensional overlap within the S-R pairs increasing dual-task costs compared to the IM-IM experiment. Alternatively, the task coherence hypothesis predicted minimal dual-task interference in the OPP-OPP experiment and an overall pattern of results similar to that observed with two IM-compatible tasks because the shared “opposite” rule required only one S-R translation for both tasks in the AND blocks. The data for the OPP-OPP experiment conformed to the latter prediction; the pattern of results was strikingly similar to the IM-IM experiment (Experiment 1).

Although the results from Experiment 3 proved problematic for the automatic activation hypothesis, both hypotheses predicted mid-range or large dual-task costs for Experiments 4 and 5 in which one task used the imitate rule and the other used the opposite rule. In these experiments, there was neither an extremely high level of dimensional overlap for both tasks nor a shared translation rule, so both hypotheses predicted interference. Surprisingly, the pattern of results looked strikingly similar for all four experiments in the 2x2. Thus, the automatic activation and task coherence hypotheses fail to account for the dramatic reduction in dual-task costs observed with two

IM tasks compared to two similar arbitrary tasks, as well as all the findings of minimal dual-task costs from Experiments 3-5 in which one or both tasks used an "opposite" mapping.

One important component of the task pairings that remained unchanged throughout Experiments 2 through 5 is the relationship between the tasks at the set level. The Opposite 2x2 manipulated the relationship between the stimuli and responses within each task and the conceptual relationship between the tasks. However, all four experiments contained very little crosstalk between the stimuli for one task and the responses for the other. In other words, both tasks used stimuli that unambiguously indicated which modality would be required to make the response; even though the mappings between the images of the hands and the correct response were incompatible in some cases, it is very unlikely that seeing an image of a hand on the screen served to activate either of the vocal responses associated with the AV task and vice versa. Accordingly, the *task set confusion* hypothesis makes predictions about the magnitude of the dual-task costs based not on the relationship between the individual stimuli and the responses or the participants' conceptualization of the task sets as belonging to the same or distinct tasks, but according to the extent to which the S-R pairs for each task can be kept separate.

The task set confusion hypothesis is based in part on set-level compatibility. Set-level compatibility is determined by the amount of correspondence between the relationships among the stimuli and responses for each task set (Fitts, 1954; Kornblum, Hasbrouq & Osman, 1990; Hazeltine et al., 2006). Put another way, this type of compatibility is determined by how closely the binding process for one S-R pair (within a task) resembles the binding process for the other S-R pair. Unlike the similarities between the stimuli and responses discussed in the previous chapter, which refer to the amount of overlap between individual elements of the S-R pairs, set-level compatibility refers to the similarity among the ensemble of S-R pairs. In order to predict the amount of dual-task interference for a given task pairing, the task set confusion hypothesis states that two tasks must not only have a high level of set-level compatibility within a task, but there must be no correspondence between the tasks. Thus, the biggest difference between the automatic activation hypothesis and the task set coherence hypothesis is that the latter claims that the S-R mappings within each task do not matter. The amount of set-level compatibility in dual-task studies may determine the ease with which the S-R pairs can be kept distinct on each trial, indicating whether dual-task interference can be avoided.

The task set confusion hypothesis makes claims about the source of dual-task costs that are similar to the output conflict described in Chapter 1 (Navon & Miller, 1987). According to Navon and Miller (1984; 1987) dual-task interference occurs due to crosstalk: processing the stimulus from one task is slowed because a stimulus used in the concurrent task is somehow related. Accordingly, both accounts emphasize the relationship between the two tasks and claim that interference arises in dual-task scenarios when there is crosstalk between one or more aspects of the tasks. The hypotheses differ with regard to the level at which the compatibility effects produce interference. Navon and Miller's (1987) output conflict was tested at the level of the individual elements of the S-R pairs. The task set confusion hypothesis claims that interference can also arise from binding issues caused by crosstalk between the task sets.

Consider the arbitrary VM task used in Experiment 6 from Halvorson et al. (2012) in which colored squares were mapped to keypresses. It is not obvious that seeing images of colored squares would require a manual response; more often, people verbally label colored objects for the purposes of classification or categorization. The arbitrary AV task in Experiment 5 from Halvorson et al. (2012) consisted of saying words in response to tones. Even though the AV task used a common modality-pairing, hearing different pitched tones does not immediately suggest making a vocal response. In fact, tones are often experienced as feedback for manual responses to things in the real world (e.g. entering an invalid password can result in an auditory response). Thus, this hypothesis claims that the dual-task interference observed when these tasks were paired with an IM-compatible task arose due to binding problems that occur when the stimuli for one task cannot be kept sufficiently distinct from the response set for the other task.

Such an account can also explain why both tasks need to be IM-compatible for dual-task costs to minimal: a single non-IM-compatible task (e.g. colored squares) may activate responses from the inappropriate set, forcing control processes to be engaged and slowing RTs. In other words, it is not only how strongly stimuli are associated with the appropriate response that determines dual-task costs; how weakly stimuli are associated with the in responses of the other task set, or the amount of output conflict, may also be critical. This is based on the notion that the process of binding the stimulus to the correct response might be more difficult if the stimulus for the other task activates information that is closely related to the information associated with the response set for the other task.

According to the task set confusion hypothesis crosstalk between the S-R pairs was not present in the IM tasks or the Opposite tasks. Even though the S-R mappings in the opposite tasks were incompatible and the tasks used a different rule, the stimuli for one task did not activate the response set for the other. In the VM tasks using images of hands, though it is possible to use the verbal labels “index” and “middle” to identify the stimulus, it does not appear to be necessary to do so. The lack of dual-task costs suggests that identifying the visual stimulus does not activate the verbal response set associated with the AV task. AV tasks consisting of saying words to words – irrespective of the individual S-R mappings – do not activate the stimuli or response set associated with the VM task. This feature of the task pairings resulted in a high amount of task set compatibility within the tasks, and importantly, caused little confusion regarding which set of responses are associated with a given stimulus. That is, the VM and AV tasks used in Experiments 2-6 produce minimal dual-task costs because there is no correspondence between the task sets; efficient dual-task performance is the result of a lack of crosstalk rather than the presence of extreme compatibility or task overlap.

In order to test this hypothesis, Experiments 7-9 constitute three of the four experiments in a 2x2 design in which the task type will be manipulated for both the VM and the AV task (see Figure 8). The fourth cell will be the IM-IM data reported in Chapter 2. The two task types will be IM and a new task type in which the input and output modalities and responses stay the same, but the visual stimuli (and necessarily the mappings) will be different. The second task type will be called paramotor (PM). This term will be used to refer to a task *pairing* in which the S-R pairs for each task contain a high amount of set-level compatibility within a task, but no crosstalk between the task sets. Because these tasks are characterized by the relationship between the S-R pairs, PM can only be used to refer to the combination of tasks in the task pairing; PM tasks are defined by the lack of correspondence between the task sets.

For the AV task in the PM pairing, the vocal responses “cat” and “dog” were randomly assigned to the auditory stimuli “green” and “red”. For the VM task in the PM pairing, participants pressed the 1 key to the hand in the shape of a “V” and the 2 key to the hand in the shape of a “W”. Although the mappings were counterbalanced across participants and varied across experiments, the actual responses were identical in all cases. This ensures that RT is not affected by greater difficulty associated with executing responses in some conditions compared to others. This 2x2 allows for systematic observation of dual-task performance when the relationship between the task sets remains constant, but the individual stimuli and S-R mappings are varied.

According to task set confusion hypothesis, there should be no crosstalk for any of the task pairings, making it easy to bind the stimulus to the correct response on each trial. The third hypothesis predicts minimal dual-task interference for all four conditions of the PM 2x2. Unlike IM-compatible tasks, the stimuli in the PM task pairings do not resemble the desired environmental outcome, or contain a high amount of dimensional overlap, so these experiments are a strong test of the claim that crosstalk between the task sets gives rise to traditional dual-task costs. This 2x2 aims to examine the magnitude of the mixing- and dual-task costs when the relationship between the stimuli and responses is not IM-compatible, and there is no shared rule between the task sets, and the separability of the S-R pairs for each task is maximized.

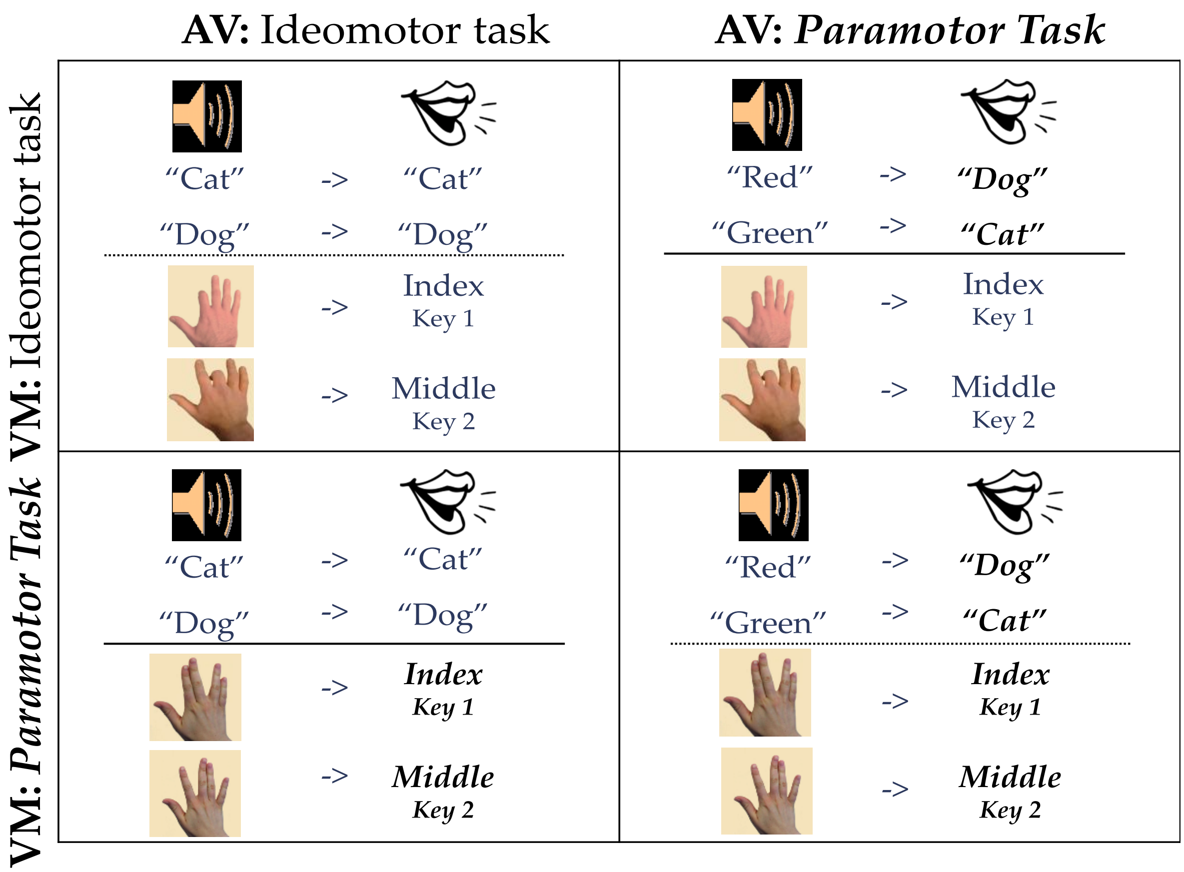


Figure 8. A diagram of the paramotor 2x2 design.

Experiments 7-9: Keeping the task sets separate

These four experiments will test the task set confusion hypothesis of dual-task interference. Methods, results and inferences for the first experiment (IM-IM, top left corner, Figure 8) were reported in Chapter 2; comparisons with the top left corner of the 2x2 design will use the data collected from that experiment.

Experiment 7: PM-PM

In the PM-PM experiment (bottom right corner, Figure 8), the visual stimuli were images of hands in the position of either a "V" (two fingers were slanted to the left and two to the right) or a “W” (two fingers were straight up in the middle with the index finger separated to the left and the pinky finger separated to the right). Otherwise, the images were the exact same dimension and color as the in the previous experiments and they were presented centrally. Participants were instructed to make a keypress with the 1 or 2 key in response to one of the images and the mappings were counterbalanced across participants. For the AV task, the vocal responses “cat” and “dog” were randomly assigned (and counterbalanced) to the stimuli “red” and “green.” The auditory stimuli were generated from the same internet source and lasting the same duration as in the previous experiment. The rest of the apparatus and stimuli, procedure, and timing of events were identical to the Experiment 1.

Experiment 8: PM-IM

In the PM-IM experiment (top right corner, Figure 8) the AV task consisted of saying “cat” or “dog” in response to hearing the words “green” or “red.” The VM task used the IM-compatible mappings from Experiment 1. Other than the stimuli for the AV task, the instructions, order of events, and responses were identical to the Experiment 1.

Experiment 9: IM-PM

In the IM-PM experiment (bottom left corner, Figure 8) the AV task used the IM-compatible stimuli and responses from Experiment 1. The VM task used the “V” and “W” images from the PM-PM experiment mapped to keypresses with the index and middle fingers. Everything else was the same as the previous experiments.

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 25) were recruited to take part in all four experiments for a total of eighty subjects. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Results and Discussion

Trials were eliminated from the analysis in the same manner as the previous experiments: the first of each block type, an incorrect response on either task, or when RTs were either too fast or too slow. Trials where RTs exceeded 1500 ms or were shorter than 150 ms were eliminated. Single task RTs are plotted according to block type for all four experiments in Figure 9.

As in the OPP 2x2, the task pairing affected overall RT; even though the exact same stimuli and responses were used across experiments, the overall time it took to respond changed depending on the task with which it was paired. Before discussing the magnitude of the mixing and dual-task costs observed in the PM 2x2, the data for each task Experiment 5 (IM-IM) and the other three experiments in this 2x2 were submitted separately to a mixed two-way ANOVA with block-type as a within-subjects factor and experiment as a between-subjects factor. The purpose of these analyses is to establish the between experiment differences in RT based on the task pairings.

Experiment 7: PM-PM

For the comparison between the IM-IM and PM-PM conditions, the ANOVA for the AV task revealed a significant main effect of block-type, $F(2,76)=37.34$, $p<.001$, $MSE=1428.79$, as well as experiment, $F(1,38)=31.31$, $p<.001$, $MSE=25462.67$.

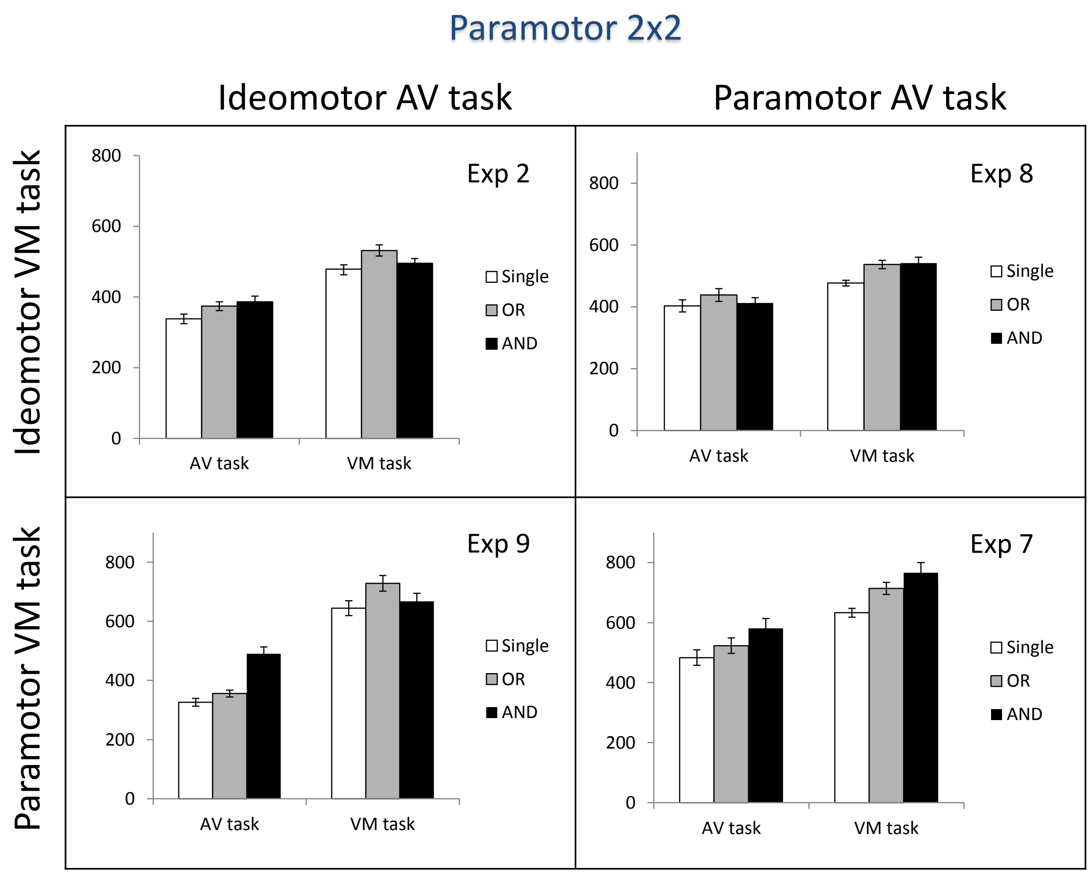


Figure 9. Findings from the paramotor 2x2.
Error bars were calculated based
on the standard error of the mean.

The interaction between block-type and experiment was also significant, $F(2,76)=5.24$, $p<.01$, $MSE=1760.00$. The same pattern was observed for the VM data. The ANOVA showed a significant main effect of block-type, $F(2,76)=20.14$, $p<.001$, $MSE=3373.08$ and experiment, $F(1,38)=76.05$, $p<.001$, $MSE=16162.10$. The block-type by experiment interaction was also significant, $F(2,76)=10.95$, $p<.001$, $MSE=5005.14$. In short, the results from the two experiments show significantly different patterns of results. RTs were different across block types, and this difference was modulated by the task pairings for the different experiments. Changing the stimuli altered the pattern of results for both tasks such that there is no longer strong evidence of perfect time-sharing. These costs will be discussed in detail in the next section. Importantly, the significant main effects of experiment indicate significantly longer overall RTs for both tasks in the PM task pairing as compared to Experiment 2. For the AV task, RTs were 163 ms slower overall for the PM task (495 ms) than the IM task, $t(59)=7.90$, $p<.001$; for the VM task (633), the difference was 202 ms, $t(59)=10.92$, $p<.001$. Participants responded much slower to the PM tasks overall than the IM tasks.

Accuracy: PM-PM

Separate ANOVAs were conducted on the accuracy data with block-type as a within-subject factor. For the AV task, accuracy was 93% and for the VM task accuracy was 97%. The ANOVA revealed a significant main effect for the AV task, $F(2,38)=9.02$, $p<.01$, $MSE=.001$. Follow-up comparisons showed that participants were significantly more accurate in the OR blocks (96%) than in the single-task blocks (93%), $t(19)=2.68$, $p<.05$, and the AND blocks (91%), $t(19)=3.30$, $p<.01$. The difference between the AND and the single-task blocks was also significant, $t(19)=2.13$, $p<.05$.

For the VM task, the ANOVA revealed a significant main effect of block-type, $F(2,38)=5.00$, $p<.05$, $MSE=.001$. Follow-up t-tests showed a significant difference between the single-task blocks (96%) and the OR blocks (98%), $t(19)=3.23$, $p<.01$, but no difference between the OR and the AND blocks (97%), $t(19)=1.67$, $p=.11$, or the AND and single-task blocks, $t(19)=1.23$, $p=.24$. As in the RT data, accuracy shows that participants performed across different block-types; interestingly, accuracy was highest in the OR blocks for both tasks, which is not consistent with a speed-accuracy trade-off since RTs from the OR blocks were in between those from the single-task and AND blocks for both tasks.

Experiment 8: PM-IM

In order to make direct comparisons between this experiment and IM-IM experiment, the data were submitted to a mixed two-way ANOVA with block-type as a within-subjects factor and experiment as a between-subjects factor separately for each task. For the AV task, the ANOVA revealed a significant main effect of block type, $F(2,76)=21.10$, $p<.001$, $MSE=674.15$, and a significant block type by experiment interaction, $F(2,76)=12.06$, $p<.01$, $MSE=635.31$. The main effect of block type reflects differences in RT across block types; the interaction shows that the pattern of results for the mixing and dual-task costs was different between experiments. These results will be discussed in more detail in the section to follow. The main effect of experiment was also significant, $F(1,38)=5.40$, $p<.05$, $MSE=14991.07$; the RTs for the AV task (418 ms) were slowed compared to the IM-IM experiment (366 ms), $t(59)=4.04$, $p<.001$. For the VM task, the ANOVA revealed a significant main effect of block type, $F(2,76)=22.38$, $p<.001$, $MSE=1457.80$, but not experiment, $F<1$. The block type by experiment interaction was significant, $F(2,76)=6.17$, $p<.05$, $MSE=1860.70$. Once again, the main effect of block type reflects differences between single, OR and AND blocks for both experiments, and the interaction suggest that changing the stimuli affected the overall pattern of results. Interestingly, in this case, the nonsignificant main effect of experiment shows that for the VM task, overall RTs were not significantly slower in this experiment than in Experiment 2.

Accuracy: PM-IM

Separate one-way ANOVAs with block-type as a within-subject factor were conducted on the accuracy data for the AV (94%) and VM (98%) tasks. The main effect of block-type was not significant for either task, $F(2,38)=1.86$, $p=.169$, $MSE=.002$ for the AV task and $F(2,38)=2.63$, $p=.085$, $MSE=.000$ for the VM task. Given that accuracy was very similar across block types, any effects in RT were likely not due to a speed-accuracy trade-off.

Experiment 9: IM-PM

As in the previous two experiments, the results from this experiment were directly compared to the IM-IM experiment. Data from the AV and VM tasks were submitted separately to a mixed two-way ANOVA with block-type as a within-subjects factor and experiment as a between-subjects factor. For the AV task, the ANOVA revealed a significant main effect of block type, $F(2,76)=87.35$, $p<.001$, $MSE=1357.95$, but not experiment, $F(1,38)=1.68$, $p=.20$, $MSE=10970.97$. The interaction between block-type and experiment was significant, $F(2,76)=33.55$, $p<.001$, $MSE=1997.84$. These significant results reflect the presence of mixing and dual-task costs and the fact that the pattern of results varied across experiments; the nonsignificant effect of experiment suggests that overall RTs for the IM AV task (405 ms) were not different from those observed in the same task when it was paired with an IM VM task. For the VM task, the ANOVA showed a significant main effect of block type, $F(2,76)=43.58$, $p<.001$, $MSE=1137.48$ and experiment, $F(1,38)=41.35$, $p<.001$, $MSE=23070.93$. The main effect of block-type reflects the significant mixing costs; follow-up t-tests show that the main effect of experiment results from significantly longer RTs in the VM task (680 ms) in this condition compared to the IM IM experiment (502 ms), $t(59)=9.97$, $p<.001$. RTs nearly doubled when a PM VM task paired with an IM AV task compared to an IM VM task paired with an IM AV task. The block-type by experiment interaction was not significant, $F<1$, suggesting a similar pattern of results for the between block comparisons for the two experiments.

Accuracy: PM-IM

Separate one-way ANOVAs with block-type as a within-subject factor were conducted on the accuracy data for the AV (96%) and VM (96%) tasks. The main effect of block-type was not significant for the AV task, $F(2,38)=1.18$, $p=.318$, $MSE=.004$, but it was significant for the VM task, $F(2,38)=9.46$, $p<.001$, $MSE=.000$. This suggests that the difference in RT for the AV task were not due to a speed accuracy trade-off, since accuracies were very similar across tasks. For the VM task, there was no difference in accuracy between the single- and AND blocks, $t<1$, but there was a difference between the single- (96%) and OR (98%) blocks, $t(19)=3.36$, $p<.01$ and the OR and AND (96%) blocks, $t(19)=4.03$, $p<.001$. This pattern is very similar to that observed in the RTs, where the shorter RTs in the single- and AND blocks have a higher error rate than the longest RTs in the OR blocks. This suggests that some of the mixing costs observed here could be due to a speed-accuracy trade-off.

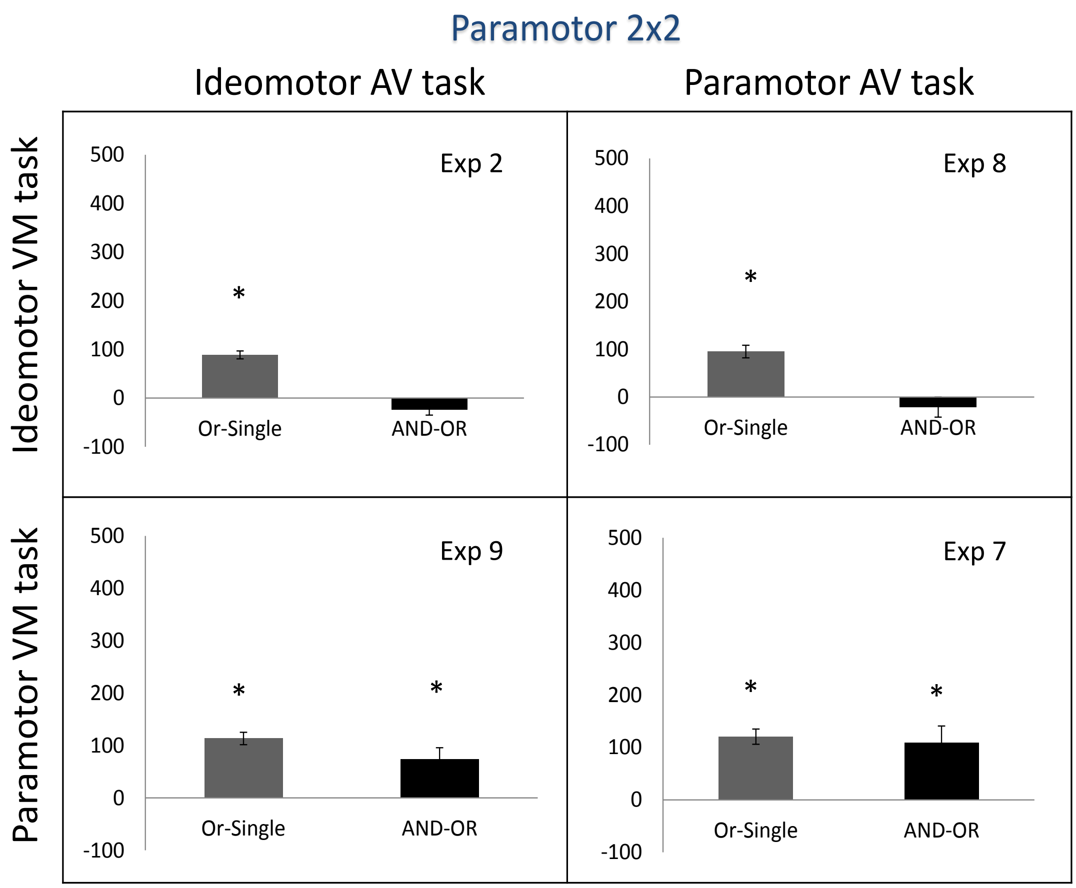


Figure 10. Sum of the mixing and dual-task costs for the paramotor 2x2.

Mixing and Dual-task Costs

The sum of the mixing and dual-task costs shown in Figure 9 reveal significantly different between block effects for PM task pairings than IM task pairings. In most cases, PM tasks result in much larger dual-task costs than two IM-tasks. For the PM-PM experiment (bottom right corner, Figure 10) the sum of the mixing costs was 121 ms, $t(19)=8.53$, $p<.001$, and the sum of the dual-task costs was 109 ms, $t(19)=3.54$, $p<.001$. The significant dual-task costs observed in this experiment suggest that the perfect time-sharing observed when both tasks were IM-compatible cannot be solely attributed to the fact that the stimuli in those tasks are unambiguously associated with the modality of the required response. As discussed previously, the RTs for both tasks were much slower overall than in the IM-IM experiment. Although Halvorson et al. (2012) and the findings from the OPP 2x2 showed that slow overall RTs does not necessarily indicate large dual-task costs, many theorists claim that dual-task costs are avoided only when the responses selection stage is sufficiently short for each task such that the central stages never overlap (e.g. Anderson et al., 2005). It is possible that the new stimuli and the mappings used in the PM task pairing increased the overall difficulty of the tasks to the extent that the separability of the tasks was no longer a critical feature for avoiding dual-task interference. However, significant differences in overall RT was not present for all between experiment comparisons in the remaining cells of the 2x2 which allows for further examination of the relationship between RT and the presence of dual-task costs.

Setting aside the differences in overall RT, one interpretation of these results is that reducing set-level interference does not alleviate performance costs associated with multi-tasking; alternatively, it is possible that instead of creating task sets in with a high set-level correspondence, the relationships between the images of hands, the “V” and the “W” shape of the fingers, and the required keypress responses and saying the words “cat” and “dog” to “green” and “red” were somehow incompatible in a way that the OPP tasks were not. In the PM VM task, for example, instead of strongly indicating the correct response modality, viewing hands with the fingers straight instead of depressed as one or more would be following a keypress may have activated response codes for incompatible movements. This possibility is addressed in the remaining cells of the 2x2. Pairing the

PM AV task, in which a pair of spoken words is arbitrarily assigned to verbal responses with different words, with the IM VM task, and the PM VM task with IM AV task will indicate whether these incompatible mappings cause interference when paired with tasks that previously lead to minimal dual-task costs. Large costs in these conditions might suggest that stimuli in these tasks activate incompatible responses that slow overall processing to such an extent that the two tasks interfere with each other.

For the PM IM experiment (upper right corner, Figure 10) the sum of the mixing costs across both tasks (95 ms) was again significant, $t(19)=7.43$, $p<.001$, but the sum of the dual-task costs (-21) was not, $t<1$. Although the ANOVAs reported in the previous section in which the data were separated by task suggested some overall differences in the between block comparisons across experiments, the pattern of results for the sum of the costs looks very similar to the IM IM experiment. In this case, pairing the PM AV task with the IM VM task did not produce the robust interference observed with the PM PM task pairing. Thus, it is possible that the interference observed in the PM PM experiment was caused by some aspect of the PM VM task.

In the PM VM task (lower left corner, Figure 10) the sum of the mixing costs was 113 ms, $t(19)=9.86$, $p<.001$, and the sum of the dual-task costs was 74 ms, $t(59)=9.86$, $p<.01$. This pattern is very similar to the PM PM experiment even though the PM VM task was paired with the IM AV task. Although none of the previous task pairings involving the IM AV task have resulted in significant dual-task interference, as shown in the RT data in Figure 9, the dual-task costs for the VM task were actually negative (-61), $t(19)=5.97$, $p<.001$, while the magnitude of the dual-task costs for the AV task (135 ms) was quite large, $t(19)=7.79$, $p<.001$. Importantly, the sum of the dual-task costs was quite large, which could be taken as evidence against the task confusion hypothesis. Alternatively, specific features of the stimuli and instructions used for the PM VM task could have caused interference between the two tasks even though the input and output modalities were distinct. These possibilities will be discussed below.

Summary

Taken together (see Figure 10), the results from this 2 x 2 show that the PM PM task pairing resulted in much larger dual-task costs than the IM-IM pairing. Interestingly, the pattern of results for the IM-PM experiment (top right quadrant), was nearly identical to that of the IM-IM experiment. As such, it seems that large dual-task costs emerge only when the PM VM task is used. The findings from the IM-PM condition in particular highlight the importance of the task pairings when measuring dual-task performance; the large costs for the IM AV task when paired with the PM VM task (bottom left quadrant, Figure 10) cannot be explained by theories of response selection in which the two tasks are processed serially and separately.

Although the PM VM task was developed with the intention of creating a VM task in which the stimulus set strongly indicated the correct response set and did not overlap with the response set for the AV task, a critical aspect of the instructions may have unintentionally introduced crosstalk between the two tasks that made the binding process difficult. When the mappings were described to the participants during instructions, the images were referred to as hands “in the shape of a “V” or “W.”” Describing the images as letters may have caused the visual stimuli to trigger the verbal label (e.g. “V”) like the colored squares in the arbitrary experiment, resulting in activation of the response set for the AV task. As such, instead of developing a task in which the stimuli gave the participant a strong indication of which type of response to make without directly signaling the correct response, the instructions may have added a verbal component to the VM task by using a verbal label for the visual stimuli. This verbal component to the VM task could have caused significant crosstalk with the AV task. This hypothesis will be taken up in a follow up experiment.

Experiment 10: Hands, not letters

To test whether the verbal label given in the instructions for the PM task pairing in Experiment 7 induced dual-task costs by creating crosstalk between the two tasks, a new VM task was designed in which images of hands were still used as the visual stimuli. For this experiment, images of hands palm up in which the fingers and thumb were all touching or spread apart in a claw-like configuration were arbitrarily mapped to keypress responses with the 1 and 2 keys on the number pad (Figure 11). The AV task was the same as the one used in the previous PM PM experiment in which the responses "cat" and "dog" were mapped to the words "green" and "red."

In addition to test the task set confusion hypothesis, this experiment also aims to test the embodied claim that seeing an image of hand automatically activates the hand of the participants, and potentially serves to facilitate manual responses (see discussion in Chapter 1). One possibility that has already been mentioned is the possibility that seeing images of hands in positions that resemble one's own hand following certain actions might trigger such a powerful imitate response that any hand position besides one compatible with the environmental outcome of the desired response will actually produce interference rather than facilitation.

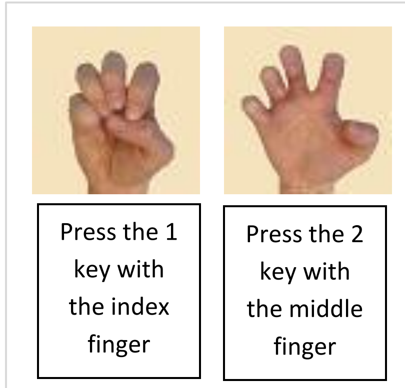


Figure 11. Stimuli and responses for the new PM-VM task.

This seems somewhat unlikely given the minimal dual-task costs observed with the OPP VM task; however, given that the hands were in positions that strongly resemble making keypresses, they may have still served to facilitate keypress responses even though the individual mappings were incompatible.

The task set confusion hypothesis predicts minimal dual-task costs with this task pairing. If dual-task interference is typically caused by binding problems that arise when the stimuli for one task set partially activate the response set for the other task, then these images of hands (provided participants are not overtly using a verbal label to identify the stimulus) should not interfere with the AV task. This is a strong test of this hypothesis; neither of the mappings contain significant amount of dimensional overlap, and are not spatially compatible in any way.

Method

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 23) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus and voice training were the same as in the previous experiment. The AV task used the same stimuli as in the PM AV task. The visual stimuli were images of a left hand facing palm up with either all the fingers and thumb touching in the center of the palm, or spread apart and bent at the middle joint (Figure 10). The other aspects of the VM stimuli including the color of the backgrounds, size, and central presentation were the same as in previous experiments.

Procedure

For the VM task, participants were instructed to press the 1 key to one of the images of the hands. In this experiment, no verbal label was used to describe the images. Participants were shown images on the computer screen, and experimenters demonstrated the position with their own hands, but were careful to not use the words "open" or "closed" to describe the hand position. For example, if the "closed" hand was mapped to the one key, participants were told that "when the hand looks like this" and then the experimenter demonstrated the correct position or pointed to an image of it, "press the 1 key." The rest of the procedure including the timing of events and block order was the same as all previous experiments.

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (5% of the remaining experimental trials) were also eliminated. Overall accuracy was 97%.

Reaction times are plotted separately for the AV and VM tasks according to block type in Figure 12. In the single-task blocks mean RTs for the AV task were 435 ms and 564 ms for the VM task. Response times for the AV task were 75 ms faster than the AV task in Experiment 1 (537 ms), $t(59)=3.79$, $p<.001$, but there was no significant difference (17 ms) in RTs for the VM task in this experiment compared to Experiment 1 (592 ms), $t(59)<1$. Thus, the tone task used in Experiment 1 was slower than the words mapped to words used here, but mapping the exact same keypresses to images of hands instead of letters did not significantly change processing time for the VM task.

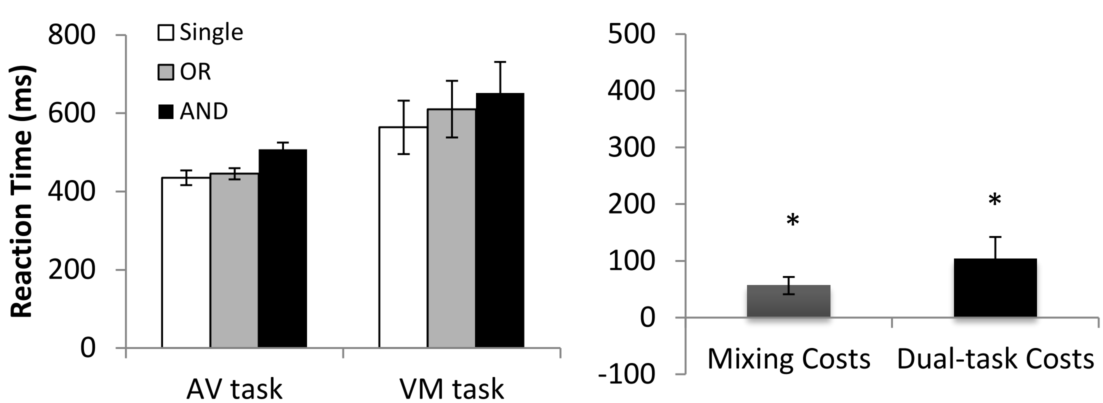


Figure 12. Findings from Experiment 10.
Left panel: mean RTs for the each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

The data from each task were submitted to separate one-way ANOVAs with block-type (single, OR, and AND) as the sole factor. For the AV task, there was a main effect of block-type, $F(2,38) = 17.22$, $MSE = 1783.89$, $p<.001$. For the AV task, RTs were not significantly different in the OR blocks (445 ms) compared to the single-task blocks (435 ms), $t<1$; RTs from AND blocks (507 ms) were significantly slower than the OR blocks, $t(19)=4.82$, $p<.001$. A slightly different pattern was observed for the VM task; once again the main effect of block-type was significant, $F(2,38) = 17.63$, $MSE = 2183.23$, $p<.001$. But for the VM task alone, the mixing costs were significant: RTs were 46 ms faster in the single-task blocks (564 ms) than the OR blocks (610 ms), $t(19) = 4.36$, $p<.001$, which were 41 ms faster than the AND blocks (652 ms), $t(19) = 2.52$, $p<.05$.

The same analysis was also conducted to compare these findings to the IM IM experiment. Data from the AV and VM tasks were submitted separately to a mixed two-way ANOVA with block-type as a within-subjects factor and experiment as a between-subjects factor. For the AV task, the ANOVA revealed a significant main effect of block type, $F(2,76)=31.92$, $MSE=1164.88$, $p<.001$, and experiment, $F(1,38)=45.68$, $MSE=1597.28$, $p<.001$. The interaction between block-type and experiment was also significant, $F(2,76)=5.30$, $MSE=6178.23$, $p<.01$. These main effects and interactions show that mean RTs and the pattern of results across block types are different for the AV task in this experiment compared to the IM IM task. Averaged across block type, overall RT was 463 ms when participants said the words “cat” and “dog” in response to the hearing the words “green” and “red;” 97 ms slower than when the task was to repeat the word (366 ms), $t(59)=7.46$, $p<.001$. Unlike the IM IM experiment in which there were significant mixing costs for the AV task, the mixing costs were not significant for the AV task alone (Figure 11, left panel). The opposite pattern was true for the dual-task costs: the AV task in this pairing showed significant costs for the AND blocks compared to the OR blocks, which was not the case for the AV IM task paired with the IM VM task.

For the VM task, the ANOVA all the comparisons were again significant. There was a main effect of block type, $F(2,76)=21.21$, $MSE=1633.50$, $p<.001$, and experiment, $F(1,38)=24.95$, $MSE=13679.51$, $p<.001$, and a significant block type by experiment interaction, $F(2,76)=11.30$, $MSE=25063.20$, $p<.01$. These comparisons show that the VM tasks showed very different patterns of results when the stimuli were changed slightly and were paired with a different AV task. The overall mean RTs were slowed significantly in this experiment; averaged across block type, the RTs for making keypresses in response to an image of a hand were 609 ms. The 107 ms difference between this and the IM VM task was significant, $t(19)=7.05$, $p<.001$. Thus, the new stimuli mapped to the exact same responses produced dramatically longer RTs. Presumably a more difficult task, when paired with the PM AV task, there was also evidence of mixing costs and dual-task costs.

In order to get a clearer picture of the overall magnitude of the between block comparisons described for each task, the sum of the mixing and dual-task costs was calculated across tasks (Figure 12, right panel). There was a significant 56 ms mixing cost overall, $t(19)=3.52$, $p<.01$, and a significant 104 ms dual-task cost, $t(19)=3.45$, $p<.01$. Thus, even though the new PM task pairing did not use instructions that overtly assigned a verbal label to the VM stimuli, the RT data shows significant performance impairment for both maintaining multiple task sets under single-task response conditions as well a cost for making two responses on each trial compared to one even when the cognitive load is held constant.

Summary

Contrary to predictions made by the task set confusion hypothesis, the PM task pairing used in Experiment 10 revealed robust mixing and dual-task costs. Importantly, the overall RTs for both tasks were significantly longer than RTs from the IM IM experiment. Although the data collected to date suggest that dual-task costs do not correlate solely with overall RT, it is possible these tasks were significantly more difficult, and that general processing was slowed to the extent that dual-task interference arose regardless of the lack of confusion between the task sets. No matter how much set-level compatibility exists within a task set and the task sets are maximally separable, one boundary condition of any dual-task hypothesis, including the task set confusion hypothesis, will likely be overall task difficulty.

However, given that the overall RTs were similar for the PM task pairings and the OPP task pairings, the possibility that viewing images of hands in positions that are incompatible with the perceptual experience associated with the required movement increases processing time and produces interference remains viable. Although the pattern of results observed with the PM task pairing cannot be accounted for by the task set confusion hypothesis, these data provide strong evidence against (a simpler version) of the embodied account of response selection, in which viewing an image of a hand facilitates manual responses.

Another possible explanation for the significant dual-task costs observed with this task pairing is that even though they were not specified in the instructions, participants were still using a verbal label to identify the stimulus, giving rise to the same crosstalk observed with the first PM task pairing. Because hands are used to communicate in so many different ways, it is difficult to find two distinct hand positions that do not contain implicit meanings yet are easily discriminable without the use of a verbal label.

General Conclusions

Taken together, the results from the PM 2x2 and Experiment 10 do not support the predictions of the task set confusion hypothesis. The task set hypothesis predicted minimal dual-task costs for the PM task pairing based on the separability of the task sets for the AV and VM tasks. Contrary to expectations, the both PM task pairings (using the “V” and “W” hands and the “open and “closed” hands) resulted in large mixing and dual-task costs. All task pairings in these five experiments also revealed robust mixing costs that appear to be independent of the magnitude of the dual-task costs. These costs are indicative of the increased load that inherently arises when the number of task pairs increases. The source of these costs will be examined in more detail in the fine-grained analyses in Chapter 7.

Only the IM IM and PM IM task pairings in the 2x2 did not produce significant dual-task interference, and the hand stimuli in Experiment 10, despite not being assigned overt labels during instruction, also did not alleviate the interference. Thus, the task set hypothesis cannot fully account for the pattern of results observed here by making predictions about interference based solely on the relationship between the input and output modalities for each task set. Instead, it appears that there may be an additional element of the binding process required for mapping the stimuli to the correct responses can also be a source of interference.

Returning once again to the arbitrary tasks in which colored squares are mapped to keypresses, it becomes more apparent that in order to select the correct keypress for the red square, for example, participants likely utilized a verbal label to bind the stimulus to the correct response (e.g. recognizing the visual stimulus as the "red" square triggered the verbal label associated with it). Not only do these verbal labels reduce the amount of correspondence within the VM task set, but they could have also resulted in partial activation of the vocal response codes required for the AV task. As such, it appears to be the case that not only must the task sets must be easily separable in terms of their input and output modalities, but also use distinct codes for binding the correct response to a given stimulus.

The notion of a central code comes from Wickens's (1984) multiple-resource theory of response selection. According to Wickens (1983; 1984), dual-task costs are largely controlled by the extent to which the central codes that mediate the S-R mappings overlap. He suggests that when S-R pairs are formed, the binding process requires participants to use central codes (C) that connect the stimulus with the response. For example, in the AV task, instead of describing the task as consisting of S-R pairs, Wickens (1984) suggests that this task consists of three parts: the auditory stimulus, a central verbal code, and the vocal response. Together, these three things make up its S-C-R mapping. The S-C-R mapping for the VM task consists of visual stimuli, spatial central codes, and manual response.

Wickens (1984) claims that dual-task interference depends critically on the type of central code required to bind the stimulus and response in *addition to* the modalities of the stimuli and responses. His theory proposes that the similarity between these central codes causes competition for another common resource that must be shared between the tasks, and is the primary source of overlap between tasks. This theory goes beyond other resource theories to suggest that the central codes interact with the stimuli and responses for each task to determine how many resources are needed. Accordingly, as long as the stimuli, central codes and responses for each task do not overlap, then no dual-task costs should be observed.

This account is consistent with the original finding of minimal dual-task costs with two IM-compatible tasks and can also account for the overall pattern of results from the PM 2x2. In that case, because the VM PM task likely required a verbal central code instead of a spatial code, there was interference between the two that was not present when the IM VM task was paired with either the IM or PM AV task. One other possibility is that the stimuli and responses used in the PM tasks may not have been sufficiently paramotor; that is, it is possible that there is a task pairing in which the stimuli exclusively activate the corresponding response set to the extent that no dual-task interference is observed. To this end, the paramotor, or task set confusion hypothesis, cannot be conclusively ruled out. However, given the difficulty of finding task pairings that meet these criteria, such a hypothesis may offer little explanatory power for future findings of minimal dual-task costs. Chapter 5 will show that task pairings which do not consist of two paramotor tasks can result in minimal dual-task interference. Furthermore, these tasks will not use images of hands, which will highlight one of the most important finding from Experiments 7 through 10: namely, simply viewing images of the body part required to make the correct response is not sufficient to eliminate dual-task costs. In other words, the fact that the visual stimuli in the experiments that have not shown significant dual-task interference so far consisted of hands cannot sufficiently explain the presence or absence of dual-task costs.

Because the OPP 2x2 used the exact same S-C-R mappings for all four conditions, none of the task sets shared stimulus modalities, central codes or response modalities. For all findings of minimal dual-task costs to date, the stimuli, central response codes (verbal and spatial), and responses do not overlap, resulting in a lack of interference between any of the stages and subsequently allowing for comparable performance when two responses are required compared to trials that require one response. In this way, the findings presented here make a novel contribution to theories of dual-task costs that will be presented in the following chapter. This hypothesis rests on the assumption that IM VM and OPP VM tasks using images of hands as stimuli require the use of a spatial central code during response selection. If this is the case, then a VM task that consists exclusively of a visual-spatial-manual S-C-R pairing should also lead to minimal dual-task costs when paired with an AV task that consists of an auditory-verbal-vocal pairing. Follow up experiments will directly test this claim.

CHAPTER V

CENTRAL CODE CROSSTALK HYPOTHESIS

The automatic activation hypothesis failed to account for the surprisingly similar pattern of results in the Opposite 2x2 when incompatible mappings were used for one or both tasks. These findings also ruled out the task coherence hypothesis, because even when each task used a different rule, dual-task costs were minimal. The task set confusion hypothesis was not supported by the findings from the paramotor task pairings used in Experiments 7-10. Although it is possible that the tasks were not sufficiently paramotor, it is clear that simply using images of hands as the visual stimuli is insufficient to eliminate dual-task costs.

Although assigning the PM hand stimuli a verbal label added an element to the VM task unintentionally, it served a critical function of illuminating the importance of the central codes required for binding the stimuli to the responses. Unlike the task set confusion hypothesis, which predicts minimal dual-task costs when there is maximal separability between the stimulus and response sets for both tasks and a high amount of correspondence among the S-R pairs in each task set, the *central code crosstalk (CCC)* hypothesis uses the concept of the central code from Wickens (1984) to illuminate an additional source of dual-task interference. If both tasks require the same central code to bind the stimulus to the response, as in the PM task pairing, dual-task costs will be large. However, if (in *addition to* using stimuli and response for each task that do not contain crosstalk) one task uses a spatial central code and the other uses a verbal central code, dual-task interference should be minimal.

Crosstalk accounts suggest that dual-task costs arise whenever some component of one task affects a variable that is relevant for performance on the other task (Navon & Miller, 1987). The amount of crosstalk present is not the same as the competition for limited resources; rather, crosstalk refers to whether an element of one task activates some element of the opposite task, thereby producing interference. Navon and Miller (1987) showed that crosstalk affects performance by causing interference when the stimuli for one of the tasks were related in a conceptual or semantic way to the stimuli for the other task.

Experiment 11: Keeping the central codes separate

The CCC hypothesis adopts the term central code from Wickens (1984) to propose a new crosstalk account. The CCC hypothesis predicts that dual-task costs are minimal only when all three components of the task: the stimuli, central codes and responses, are distinct. If there is crosstalk between any of the elements of the S-C-R codes between the two tasks, large dual-task costs will be observed. To test this account, Experiment 11 will use AV and VM tasks that use distinct central codes – verbal and spatial, respectively – without using images of hands as the stimuli for the VM task.

Methods

Participants

Twenty-six undergraduates from the University of Iowa (ages 19 – 25) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus was the same as the previous experiments. The visual stimuli consisted of two colored circles subtending 2.07° x 2.07° centered on the horizontal axis, spaced equidistant within the same 6.7° by 6.6° neutral colored rectangle, which was framed by a black background. On each trial, one of the circles was yellow and the other was blue. The stimuli were assigned to a spatially corresponding response with the 1 or 2 key on the number pad. The auditory stimuli were the words “cat” and “dog;” the task was to repeat the word that was presented in the headset. Everything else about the display and equipment was identical to the previous experiments.

Procedure

For the VM task, half the participants were instructed to make responses based on the location of the blue circle. In this condition, if the blue circle was on the left side of the display the correct response was a keypress of the 1 key on the number pad with the right index finger, and if the blue circle was on the right the correct response was a keypress of the 2 key with the right middle finger. Counterbalancing the mapping ensured that there was nothing special about responding to a blue circle versus a yellow circle, or vice versa. Responses must be made based on the spatial compatibility between the target side and the response side. The AV task was identical to the shadowing task used in Experiment 2. The rest of the procedure including the timing of events and block order was the same.

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms

(5% of the remaining experimental trials) were also eliminated. Overall accuracy was 98%.

Overall mean RTs for the AV task were 327 ms and 441 ms for the VM task. Reaction times are plotted separately for the AV and VM tasks according to block type in Figure 13. The mean RTs for each task were compared to the IM-compatible tasks used in Experiment 2. For the AV task, RTs were 40 ms faster overall in this experiment than when the when the exact same task was paired with the IM VM task, $t(44)=3.86$, $p<.001$. Mean RTs for the VM task were also faster in this experiment; when the colored circle stimuli were mapped to the exact same responses as the images of hands, overall RTs were 61 ms faster than in Experiment 1, $t(44)=6.39$, $p<.001$.

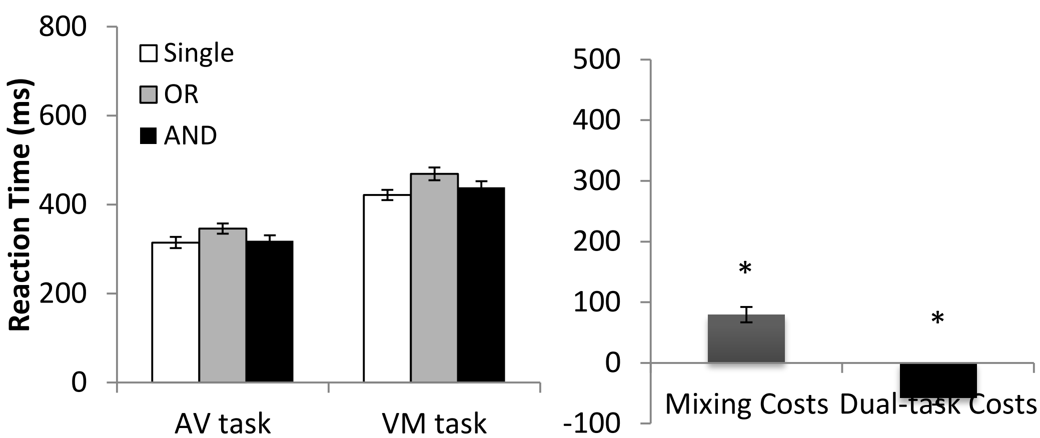


Figure 13. Findings from Experiment 11.
Left panel: mean RTs for the each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

Although these comparisons are between-subject, it is interesting to speculate about possible explanations for the changes in RT for the single-task blocks. The difference in RT for the VM tasks could reflect a difference in the amount of time it took to encode the visual stimuli; the images of hands are visually more complex. Although the longer duration of the encoding stage did not cause dual-task interference in Experiment 1, it could be taken as further evidence against the embodied claim that manual responses are facilitated with the hand stimuli because of the overlap in the body part seen on the screen and used to execute the response. The difference in RT for the AV task is also interesting because it was the exact same shadowing task in both experiments; overall RT for each task appears to be influenced by the task pairing. This task pairing resulted in faster overall RTs for both tasks.

Accuracy

Separate one-way ANOVAs with block-type as a within-subject factor were conducted on the accuracy data for the AV (97%) and VM (99%) tasks. The main effect of block-type was marginally significant for the AV task, $F(2,38)=2.95$, $p=.06$, $MSE=.001$, and significant for the VM task, $F(2,38)=3.90$, $p<.001$, $MSE=.000$. This suggests that any difference in the RTs by block for the AV task were not solely due to a speed accuracy trade-off, since accuracies were very similar across tasks (single=94%, OR=99%, AND=96%). For the VM task, accuracies were very similar across block types although some of the between block comparisons revealed significant difference. Accuracy in the single task blocks (98.67%) was slightly lower than in the OR blocks (99.23%), $t(19)=2.33$, $p<.05$, as well as the AND blocks (99.12%), $t(19)=2.36$, $p<.05$.

There was no difference between the OR and AND blocks, $t<1$. Although there appears to be a very small difference between the single task blocks and the other two, it is unlikely that this led to a significant speed-accuracy trade-off responsible for the observed interference. Overall, the accuracy was very high for both tasks.

Mixing and Dual-task Costs

Between block comparisons were calculated for both tasks; the right panel of Figure 13 shows the sum of the mixing and dual-task costs. As in all other experiments reported here, significant mixing costs were observed. In the OR blocks, RTs were 79 ms slower than the single-task blocks, $t(25)=6.35$, $p<.001$. There was also a significant difference between the AND and the OR blocks, although it reflects a negative dual-task cost. Response times were 66 ms faster in the AND blocks than the OR blocks even though participants were required to make two responses instead of one, $t(25)=6.60$, $p<.001$. The CCC hypothesis predicted no dual-task interference for this task pairing; previous experiments have shown evidence of small negative dual-task costs, and the difference between the AND and the OR blocks in this experiment is quite large. The CCC hypothesis does not currently offer an obvious explanation for the large negative dual-task cost; however, it is possible that the fine-grained analyses in Chapter 7 will offer some insight into whether this task pairing was significantly more affected by switch or load costs than other task pairings, or whether exact repetitions in dual-task blocks were significantly faster than repetitions.

Summary

The AV and VM tasks that comprised the task pairing in Experiment 11 used distinct input and output modalities, as well as distinct central codes. The AV task required a verbal central code for binding the stimulus to the correct response, whereas the VM task required a spatial central code. The VM task did not contain images of hands, and clearly do not meet the criteria for IM-compatibility. Because the location of the target stimulus was spatially compatible with the location of the correct response, even though the VM task used images that contained colors, naming or identifying the target with a verbal label was not necessary for binding the stimulus to the correct response, thus, there was no interference between the two tasks. Once again, the mixing costs were significant; this suggests that there is a persistent, robust cost in dual-task scenarios associated with the increased cognitive load inherent to adding a second S-R pair. Whether the mixing costs are influenced more heavily by costs associated with switching between tasks in the OR blocks, or the increased cognitive load will be taken up in the fine-grained analyses in Chapter 7. The influence of these two costs on the overall mixing cost is likely dependent on the particular task pairing. Understanding the relationship between the two tasks, or the task pairing, is critical for making claims about any of the measurable costs in dual-task paradigms.

Obviously, whether the S-C-R pairs require the same central code can only be determined when both of the tasks in the pairing are considered. However, there is one notable feature of all the tasks pairings that have resulted in minimal dual-task costs to this point: all pairings contained an AV task that consisted of saying words in response to words. Although an AV task in which any word stimuli are mapped to vocal responses with different words is clearly not a sufficient condition of a task pairing that leads to minimal dual-task costs (see e.g., Experiment 10), it is possible that it is a necessary condition because only AV tasks consisting of words-to-words contain an exclusively verbal central code.

At least two central codes have been proposed: spatial and verbal. Previous experiments have shown that when a verbal label is required to bind the visual stimuli to the manual responses, the two tasks interfere. It is also possible that only AV tasks using words as stimuli and responses exclusively use a verbal central code; the high and low tones mapped to words in the arbitrary AV task (Experiment 2) could have included a spatial central code. If determining the identity of the tone by comparing it to the other stimulus in the set activated a spatial central code in the process of binding it to the response, it could have resulted in interference with the VM task. To test the possibility that only AV tasks in which words are mapped to words use an exclusively verbal central code, Experiment 12 will use new stimuli that are non-words but do not require comparison within the stimulus set to choose the correct response.

Experiment 12: Is saying words to words special?

Experiment 12 will test one of the boundary conditions of the CCC hypothesis by using an AV task that does not consist of saying words in response to spoken words. Instead, the AV task used in this experiment will consist of two easily discriminable, non-word auditory stimuli. The stimuli are a bell sound that resembles an old-fashioned alarm clock, and a whistle sound that resembles the sound of referees' or coaches' whistles. The responses were the words "cat" and "dog" arbitrarily mapped, and counterbalanced, to the two stimuli. This AV task uses the same S-C-R codes as the AV shadowing task and the PM AV task. The VM task will be the same spatial task used in

Experiment 10. The CCC hypothesis predicts minimal dual-task interference for this task pairing.

Methods

Participants

Twenty undergraduates from the University of Iowa (ages 19 – 25) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus was the same as the previous experiments. The visual stimuli were identical to those used in the previous experiment. The auditory stimuli consisted of two sounds downloaded from an online database edited to last the same duration as the spoken words used in previous experiments (250 ms). One of the stimuli was a bell sound, similar to the trilling of an old-fashioned alarm clock, and the other stimulus was a whistle sound that strongly resembled a coach's whistle. The responses "cat" and "dog" were arbitrarily assigned to one of the stimuli and counterbalanced across participants. The mappings for the VM task were also counterbalanced across participants such that there were 4 total conditions, each of which contained 5 participants. Everything else about the display and equipment was identical to the previous experiments.

Procedure

The VM task and instructions was identical to the previous experiment. Depending on the assigned mapping, participants were told to say the word "cat" in response to the sound of the whistle, and the word "dog" in response to the bell.

Researcher assistants stayed in the room for the practice block of the AV task to ensure that participants were saying the correct word in response to the stimulus. The rest of the procedure including the timing of events and block order was the same.

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (5% of the remaining experimental trials) were also eliminated. Overall accuracy was 97%.

This task pairing resulted in dramatically slower overall RTs compared to previous experiments.

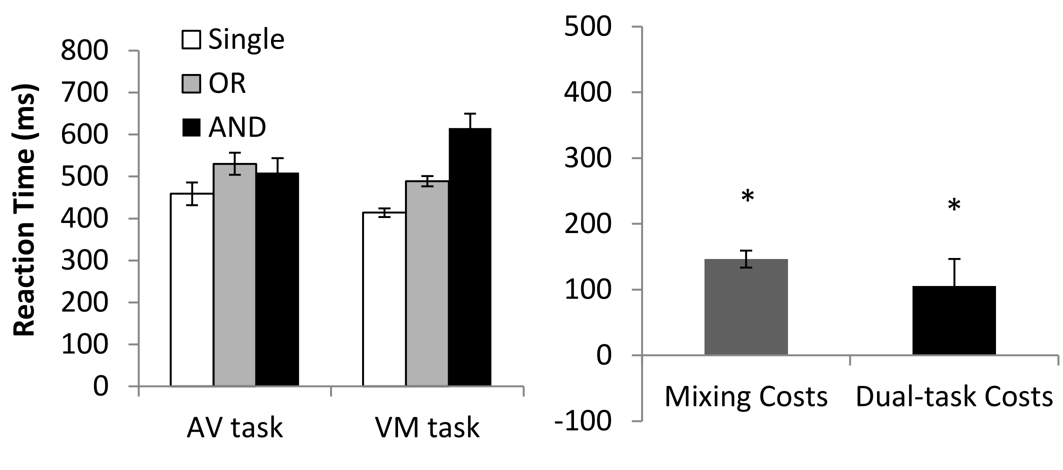


Figure 14. Findings from Experiment 12.
Left panel: mean RTs for the each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

For the AV task, overall mean RTs were 500 ms and 506 ms for the VM task. This task pairing resulted in the most similar RTs across tasks of all the pairings used so far. Thus, theories of response selection that assume instances of perfect time-sharing are the result of strategic, serial scheduling of the stages for each task or greedy recruitment of resources as a result of one task taking significantly less time to complete will have a difficult time accommodating findings of minimal dual-task cost in this experiment.

Compared to the previous experiment, the mean RTs for the exact same task VM task (441 ms) paired with a vocal shadowing task were 65 ms slower in this experiment, $t(44)=4.28$, $p<.001$. Changing the stimuli associated with the exact same vocal responses from words to sounds also significantly slowed down mean RTs for the AV task in this experiment compared to the shadowing task in Experiment 10 (327 ms). Mean RTs were substantially slower (173 ms) in this experiment, $t(44)=14.99$, $p<.001$. Thus, the AV task using non-word stimuli resulted in significantly slower overall RTs not only for the AV task, but also for the exact same spatial VM task.

Accuracy

Separate one-way ANOVAs with block-type as a within-subject factor were conducted on the accuracy data for the AV (94%) and VM (99%) tasks. The main effect of block-type was not significant for the VM task, $F<1$, but it was significant for the AV task, $F(2,38)=12.43$, $p<.001$, $MSE=.001$. For the AV task, percent correct was highest in the OR blocks. Compared to the single task blocks (94%), accuracy was significantly higher in the OR blocks (97%), $t(19)=3.11$, $p<.01$, which was also higher than the AND blocks (93%), $t(19)=5.55$, $p<.001$. There was no difference between percent correct for the single and AND blocks, $t(19)=1.58$, $p=.13$. This pattern resembles that observed in reaction time, where the shortest RTs were observed in the single- and AND blocks. This pattern was not observed for RTs in the VM task, which also showed no significant difference in accuracy. Thus, although the mixing costs observed in the AV task could have been slightly inflated due to a speed-accuracy trade-off, it does not appear that such a trade-off could account for the whole pattern of costs observed here.

Mixing and Dual-task costs

In this experiment, the sum of the mixing costs for the two tasks (146 ms) was significant, $t(19)=11.68$, $p<.001$. As shown in Figure 14, right panel, the sum of the dual-task costs (106 ms) was also significant, $t(19)=2.58$, $p<.05$. Thus, at first glance, in addition to resulting in large mixing costs, replacing the word stimuli in the AV task with sounds increased the sum of the dual-task costs across tasks. However, an interesting pattern emerged when the sum of the dual-task costs were measured separately for each subject. Appendix A (beginning on page 168) contains figures of the sum of the dual-task costs separated by subject for Experiments 1-3, 7, and 10-14. For Experiment 12, there is a noticeably different pattern of results than experiments that resulted in a similar magnitude of dual-task costs (e.g., Experiment 2, 185 & Experiment 10, 106 ms) as well as experiments that resulted in minimal dual-task costs (e.g., Experiment 1, -24 ms & Experiment 3, 10 ms). Unlike Experiment 2, in which nearly every participant (19 out of 20) showed a positive dual-task cost with a magnitude greater than 50 ms, nearly half (9 out of 20) showed a dual-task cost of less than 50 ms or even a negative cost. In Experiment 10, in which the overall magnitude of the dual-task costs was identical to the cost observed in this experiment, the costs by participant were again much more homogenous. All participants showed a positive dual-task cost, and for a majority (15 out 20) of the participants the cost was 50 ms or greater. Thus, even though the overall magnitude of the dual-task costs was quite large, the pattern was quite different across individual participants.

Summary

Experiment 12, in which the words “cat” and “dog” were mapped to auditory stimuli that were not words, resulted in significant mixing and dual-task costs. However, this pattern of results was observed for less than half the participants. There was a clear divide in the magnitude of the dual-task costs such that 9 out of 20 participants had a dual-task cost of less than 50 ms, while the cost for the remaining 11 was over 50 ms. This makes the theoretical interpretation of the results from this experiment a bit murky. On the one hand, the overall magnitude of the dual-task costs clearly shows evidence of interference for this task pairing. On the other hand, a closer look at the costs for the individual subjects shows that roughly half were able to perform these two tasks simultaneously almost as efficiently as performing each task individually. Because over half the participants did not show significant dual-task costs, it does not appear that only AV tasks consisting of words mapped to words lead to findings of minimal dual-task costs. However, more participants showed large dual-task costs than in Experiment 11 (dual-task costs were greater than 0 ms for only 1 out of 20 participants), in which the verbal shadowing task was paired with the same spatial VM task. Perhaps the longer RTs for the AV task encouraged more of the participants to adopt a serial response strategy in the AND blocks.

Experiment 13: Non-standard modality pairings

Although the sum of the overall dual-task costs was significant, half of the participants in Experiment 12 showed little evidence of interference even when the AV task did not consist of saying words and the VM task did not use images of hands as stimuli. This suggests that verbal shadowing tasks are not the only type of AV task that can be performed simultaneously with a VM task; so long as the central codes do not overlap, some participants are capable of highly efficient dual-task performance. In Experiments 1 through 12, the responses were kept identical for the AV and VM tasks, and the relationship between the tasks was altered by using novel stimuli and S-R mappings. Even though the responses were kept constant, these changes created a much wider variety of tasks and task pairings than has previously been used in this type of dual-task paradigm and shown to produce minimal dual-task interference (see Table 2). However, the critical feature of the CCC hypothesis is that the central codes of the two tasks must be distinct. Thus, there is an even broader range of task pairings that could potentially lead to minimal dual-task costs.

The aim of this experiment is to test another boundary condition of the predictions made by the CCC hypothesis; the CCC hypothesis predicts minimal dual-task interference when one task uses a verbal central code and the other task uses a spatial central code. Even though non-standard modality pairings often result in increased dual-task interference (see e.g., Shaffer, 1975; Wickens, Sandry, & Vidulich, 1983), it is possible for two tasks with non-standard modality pairings to also have distinct central codes. Previous tests of the influence of non-standard modality pairings on dual-task interference have often introduced input and output conflicts with the non-standard pairs that were not present with the standard pairs. Thus, this experiment will use two tasks with non-standard modality pairings that have distinct central codes – spatial and verbal – to test the extent to which the central code influences the magnitude of the dual-task interference.

Methods

Participants

Twenty-four undergraduates from the University of Iowa (ages 19 – 23) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus and voice training were the same as in the previous experiments. All the stimuli in this experiment were used in one of the previous experiments. The auditory stimulus was the low tone from Experiment 2 presented in only one of the earphones on each trial. The visual stimuli were the words “cat” and “dog,” printed in capital letters in a gray 6.7° x 6.6° rectangle, framed by a black background. The words were black and subtended 4.8° x 1.72° within the gray rectangle. The rest of the apparatus and display was the same as in previous experiments.

Procedure

For the VV task, participants were instructed to say the word that was presented on the screen just as they would read something aloud. So, for example, if the word “cat” appeared, the correct response was to say “cat.” For the AM task, participants were instructed to press the 1 (left) or 2 (right) key on the number pad that was spatially compatible with the location of the presentation of the tone. If the tone sounded in the left ear, participants were instructed to press the 1 key; if it was in the right ear, they should press the 2 key. The rest of the procedure including the timing of events and block order was the same as all previous experiments.

Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (4% of the remaining experimental trials) were also eliminated. Overall accuracy was 97%.

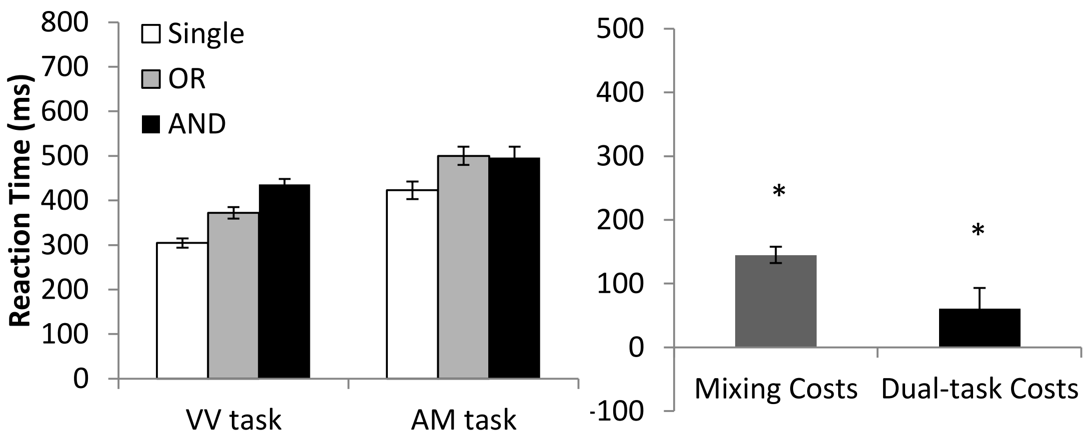


Figure 15. Findings from Experiment 13.
Left panel: mean RTs for the each task separated by block type.
Right panel: sum of the mixing and dual-task costs across both tasks.
For both figures, error bars were calculated based on standard error of the mean.

Somewhat surprisingly, mean RTs across block type for each task were surprisingly fast given that the tasks used non-standard modality pairings. Overall mean RTs in the VV task were 371 ms and 473 ms for the AM task. Compared to Experiment 11, in which there was no evidence of dual-task interference with the shadowing AV task and the spatial VM task, the task with the same response modality in this experiment (VV task) was 44 ms slower than the AV task in Experiment 11, $t(44)=4.06$, $p<.001$. Compared to the VM task in Experiment 11, RTs in the AM task were 32 ms slower, $t(44)=2.43$, $p<.05$. Compared to Experiment 2, the VV task was 160 ms faster than the AV task in which tones were mapped to words, $t(19)=10.39$, $p<.001$, and the AM task was 118 ms faster than the VM task in which colored squares were mapped to keypresses, $t(19)=5.91$, $p<.001$.

Accuracy

Separate one-way ANOVAs with block-type as a within-subject factor were conducted on the accuracy data for the VV (95%) and AM (98%) tasks. The main effect of block-type was not significant for the VV task, $F(2,38)=2.47$, $p=.10$, $MSE=.002$, but it was significant for the AM task, $F(2,38)=7.97$, $p<.01$, $MSE=.001$. For the AM task, percent correct was highest in the OR blocks. Compared to the single task blocks (98%), accuracy was significantly higher in the OR blocks (99%), $t(19)=2.78$, $p<.05$, which was also higher than the AND blocks (98%), $t(19)=4.66$, $p<.01$. There was no difference between percent correct for the single and AND blocks, $t(19)=1.28$, $p=.22$. Given the similarity in accuracy across block types, it is not likely that the patterns of results observed in RT are driven solely by a speed-accuracy trade-off.

Mixing and Dual-task costs

In this experiment the sum of the mixing costs (145 ms) was significant, $t(19)=11.11$, $p<.001$, as was the sum of the dual-task costs, 61 ms, $t(19)=2.77$, $p<.05$. As in the previous experiment, less than half the participants showed a dual-task cost of over 50 ms, even though the overall sum of the costs was significant (see Appendix A). Compared to the more homogenous findings of experiments that resulted in minimal dual-task costs for all subjects (e.g. Experiment 12) or robust dual-task costs for all subjects, the findings from this experiment suggest that some participants may be adopting a serial strategy whereas others are more willing to make two responses simultaneously. Given that non-standard modality pairings can result in larger dual-task costs (see e.g. Hazeltine et al., 2006), these results that under some conditions, when there is no conflict between input and output modalities as well as central codes, highly efficient dual-task performance is possible.

Summary

Even though non-standard modality pairings often result in large dual-task costs, these two tasks produced very fast RTs within each task and although the mixing and dual-task costs were significant overall, half of the participants showed little evidence of interference. At this point, researchers do not have an agreed upon explanation for why some individuals are more “willing” to make two responses simultaneously than others, although this phenomenon has been demonstrated in previous dual-task studies (see e.g. Schumacher et al., 2001). In this experiment, for approximately half the participants, these two tasks did not result in significant performance impairments during dual-task trials. Thus, the results provide some evidence in support of the CCC hypothesis; when the central codes for the two tasks are distinct, even if non-standard modality pairs are used, RTs are not significantly slowed for two responses compared to one.

None of the previously considered hypotheses could account for the pattern of results observed here. Instead, the data support the predictions of the CCC hypothesis; when one of the central codes is verbal and the other is spatial, and there was no other input or output interference, very minimal dual-task costs were observed with a measure in which the cognitive load was kept constant. Moreover, the results from these studies underscore one of the major findings from Halvorson et al. (2012): the magnitude of the dual-task interference can only be predicted when both tasks in the pairing are considered. The results from these experiments show that when one of the task sets in a dual-task situation uses exclusively spatial information and the other verbal, then the two tasks can be performed simultaneously without interference and dual-task costs can be avoided. Although not commonly discussed in the dual-task literature, theories of working memory in which separate systems are postulated for verbal and spatial tasks offer a viable framework for how these two types of tasks can be kept separate (see e.g. Baddeley, Grant, Wight, & Thomson, 1975). This possibility will be taken up in more detail in the final summary chapter.

Before discussing the fine-grained analyses and the overall conclusions, Chapter 6 will test a critical question regarding the level at which crosstalk between the two tasks leads to dual-task interference.

CHAPTER VI

AT WHAT LEVEL(S) DO THE TASKS INTERACT?

In addition to the novel findings of minimal dual-task costs with multiple task pairings and S-R mappings presented here, the previous thirteen experiments illuminated a critical feature of dual-task performance: the magnitude of the costs is dependent on the task pairing. The amount of interference depends on the interaction between the central codes for each task. Moreover, the task pairing appears to affect not only performance on dual-task trials, but even performance on each task separately. The overall RT for one or both of the tasks (even in single task blocks) has been shown to depend on the task with which it is paired. This suggests that requiring participants to maintain and perform multiple tasks changes the way the tasks are conceptualized, which affects performance throughout the experiment, even on trials in which only one response is required.

This feature of dual-task experiments raises an interesting question about the locus of the dual-task interference. In all the previous experiments, the amount of crosstalk between the central codes was kept constant for all the S-R pairs in the tasks. Although there is a possibility that certain trial types, exact repetitions for example, might decrease response time compared to partial repetitions, none of the experiments reported here have manipulated whether dual-task costs are affected by the amount of crosstalk present among all the S-R pairs for both tasks or if dual-task costs are dynamically determined based on the presence or absence of crosstalk in a given trial. This question will be examined in Experiment 14.

Experiment 14: At what level does crosstalk produce

dual-task costs?

The aim of this experiment is to test whether dual-task costs are determined by whether crosstalk is present between the central codes for each task pairing on the current trial or whether the presence of crosstalk between any of the central codes in the task pairing will result in dual-task costs. To address this question, the AV and VM tasks used in this experiment will contain one S-R pair from a task pairing that did not lead to dual-task costs and one arbitrary S-R pair that led to significant interference. One possibility is that dual-task interference arises dynamically during the binding process for a given trial. In that case, dual-task costs should only be present on trials in which the central codes for the S-R pairs interfere. Alternatively, robust dual-task costs could be observed across all trial types. This would suggest that dual-task costs are determined by the relationship between all the S-R pairs in the task pairing, and that

Methods

Participants

Twenty-four undergraduates from the University of Iowa (ages 19 – 25) were recruited to take part in this experiment. Individuals participated in partial fulfillment of a requirement for an introductory course and reported normal or corrected-to-normal vision and hearing.

Stimuli and Apparatus

The apparatus and the visual stimuli were identical to those used in the previous experiment. The auditory stimuli consisted of two sounds downloaded from an online database edited to last the same duration as the auditory stimuli used in previous experiments (250 ms). One of the stimuli was a bell sound, similar to the trilling of an old-fashioned alarm clock, and the other stimulus was a sound that strongly resembled a coach's whistle. The responses "cat" and "dog" were arbitrarily assigned to one of the stimuli and counterbalanced across participants. The mappings for the VM task were also counterbalanced across participants such that there were 4 total conditions, each of which contained 5 participants. Everything else about the display and equipment was identical to the previous experiments.

Procedure

The VM task and instructions was identical to the previous experiment. Depending on the assigned mapping, participants were told to say the word "cat" in response to the sound of the whistle, and the word "dog" in response to the bell. Research assistants stayed in the room for the practice block of the AV task to ensure that participants were saying the correct word in response to the stimulus. The rest of the procedure including the timing of events and block order was the same.

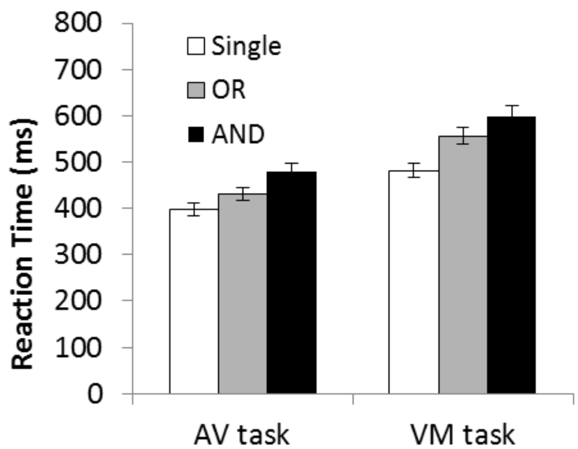
Results and Discussion

The first of each block-type was considered practice and eliminated from the analysis. Trials were also eliminated from the analysis when an incorrect response was made on either task. Trials where RTs exceeded 1500 ms or were shorter than 150 ms (10% of the remaining experimental trials) were also eliminated. Overall accuracy was 95%. Mean RT for each task separated by block type is plotted in Figure 15.

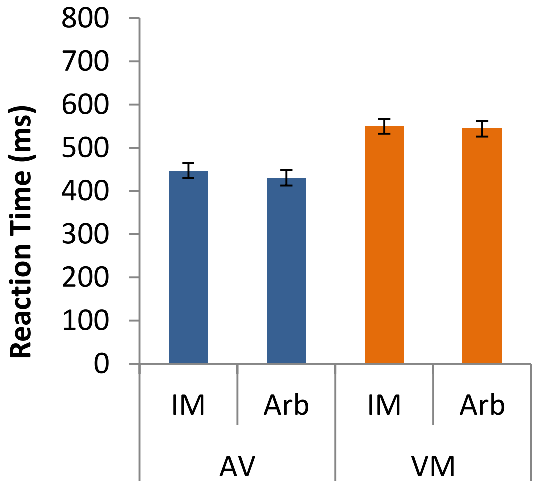
Overall mean RTs for the AV task were 435 ms and 546 ms for the VM task. Compared to Experiment 2, in which both S-R pairs for the AV and VM tasks were IM-compatible, RTs were 60 ms slower in the mixed AV task, $t(130)=5.24$, $p<.001$, and 33 ms slower in the mixed VM task, $t(130)=2.94$, $p<.01$. Mean RTs were slightly slower overall in this experiment than Experiment 1; compared to Experiment 1 (arbitrary S-R pairs), mean RTs from the AV task were 102 ms faster in this experiment, $t(130)=5.59$, $p<.001$, and mean RTs from the VM task were 46 ms faster, $t(130)=2.36$, $p<.05$. Thus, it is unlikely that costs observed in this experiment are due solely to an increase in overall RT or task difficulty.

Mean RTs were also calculated for each task based on trial type. Overall RTs for each S-R pair averaged across block type were calculated separately for each task (see Figure 16, panel b). For the AV task, RTs to the “cat”-“cat” pairing (447 ms) were actually 17 ms slower than the tone-“dog” pair (431 ms), $t(23)=1.10$, $p=.28$. For the VM task, RTs to the hand stimulus (549 ms) were 5 ms slower than RTs to the colored square (544 ms), $t<1$. Thus, within each task, there was no difference in overall response time for the IM-compatible S-R pair compared to the arbitrary S-R pair.

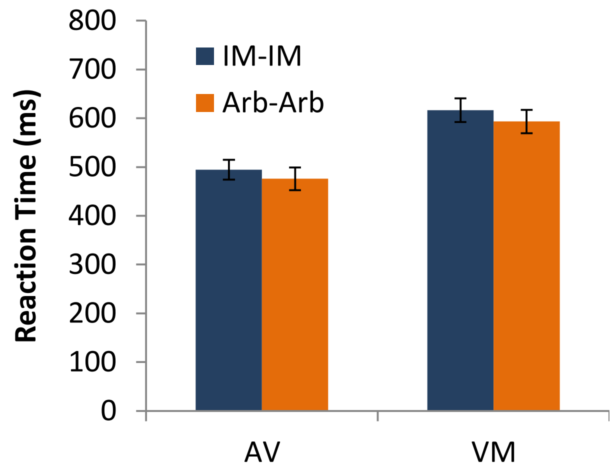
Lastly, mean RTs from the AND blocks were calculated for each task, separated by trial type (Figure 16, panel c). Only the trials in which both S-R pairs were IM-compatible or both S-R pairs were arbitrary were used for this comparison. The IM-IM trials are identical to some of the trials from Experiment 2 whereas the Arb-Arb trials are very similar to those in Experiment 1. Although the overall mean RTs were different for Experiments 1 and 2, for the AV task, there was no significant difference between trials in which the S-R pair for both tasks was IM-compatible (495 ms) and trials with two arbitrary S-R pairs (476 ms), -17 ms, $t(23)=1.23$, $p=.23$. Likewise, for the VM task, the difference between RTs for the IM-IM trials (617 ms) and Arb-Arb trials (593 ms) was not significant, -23 ms, $t(23)=1.85$, $p=.08$. Interestingly, even though the differences were not significant, for both tasks the IM-IM trials were actually slightly slower than the Arb-Arb trials.



(a)



(b)



(c)

Figure 16. Findings from Experiment 14.
(a) Mean RTs for the each task separated by block type.
(b) Mean RTs across blocks for each task according to the S-R pair.
(c) Mean RTs from AND blocks for IM-IM and Arb-Arb pairs for each task.
For all figures, error bars were calculated based on standard error of the mean.

Accuracy

Separate ANOVAs were conducted on the accuracy data with block-type as a within-subject factor. For the AV task, accuracy was 93% and for the VM task accuracy was 98%. The ANOVA revealed a significant main effect for the AV task, $F(2,46)=5.86$, $p<.01$, $MSE=.001$. Follow-up comparisons showed that the difference between the OR blocks (95%) and the single-task blocks (93%) was not significant, $t(23)=1.68$, $p=.11$; likewise for the difference between the single-task and the AND blocks (91%), $t(23)=1.45$, $p=.16$. The difference between the OR and the single-task blocks was significant, $t(19)=3.68$, $p<.01$.

For the VM task, the ANOVA revealed a significant main effect of block-type, $F(2,46)=12.56$, $p<.001$, $MSE=.000$. Follow-up t-tests showed a significant difference between the single-task blocks (97%) and the OR blocks (99%), $t(24)=5.02$, $p<.001$, and between the OR and the AND blocks (97%), $t(23)=3.97$, $p<.001$. There was no difference between the AND and single-task blocks, $t(23)=1.11$, $p=.28$. As in the RT data, accuracy shows that participants performed across different block-types; accuracy was highest in the OR blocks for both tasks, which is not consistent with a speed-accuracy trade-off since RTs from the OR blocks were in between those from the single-task and AND blocks for both tasks.

Mixing and Dual-task Costs

As shown in Figure 17 (left panel), the mixing and dual-task costs were significant for both tasks. The sum of the mixing costs across both tasks was 108 ms, $t(23)=8.46$, $p<.001$, and the sum of the dual-task costs was 90 ms, $t(23)=3.84$, $p<.001$. In order to obtain a measure of the critical comparison in this experiment (dual-task cost by trial type), the same between-block comparisons were calculated for the IM-IM trials and Arb-Arb trials separately (Figure 17, right panel).

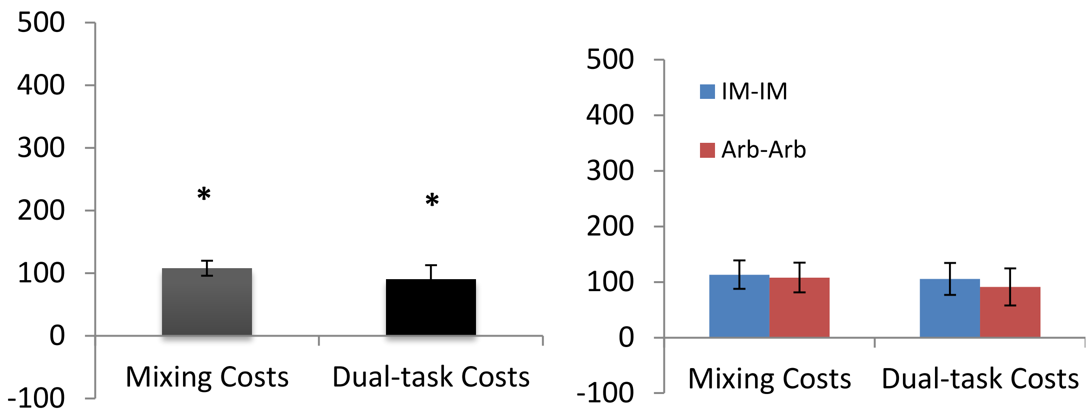


Figure 17. Mixing and dual-task costs.
Left panel: sum of the mixing and dual-task costs across both tasks.
Right panel: sum of costs across both tasks separated by trial type.
For both figures, error bars were calculated based on standard error of the mean.

To calculate the IM-IM mixing costs, the IM-compatible trials from the single-task blocks were subtracted from the IM-compatible OR trials. These costs (113 ms) were not different from the difference between the arbitrary OR trials compared to the arbitrary single trials (108 ms), $t<1$. The dual-task costs were calculated by comparing only the AND trials in which both tasks were IM-compatible to the IM-compatible OR trials and only the trials from the AND blocks in which both tasks were arbitrary to the arbitrary OR trials. For the IM-IM condition, dual-task costs were 105 ms, which was not different from the 91 ms cost observed with the arbitrary pairs, $t<1$. This striking similarity between the magnitudes of the costs regardless of the trial type shows that dual-task interference arises even when the particular combination of S-R pairs on a given trial did not result in dual-task costs in a previous experiment.

Summary

These findings offer novel insight into the source of dual-task interference between two tasks. The findings from this experiment showed that when any of the S-R pairs for the two tasks require the same central code, interference will occur between the two tasks. In other words, dual-task costs are not determined by whether there is crosstalk between the central codes for the two tasks on a given trial; instead, any overlap between the components of all the S-R pairs for each task will result in significant dual-task interference on all trials.

CHAPTER VII

FINE-GRAINED ANALYSES

The purpose of this chapter is to delve into the RT differences across task pairings based not only on the difference between block types, but also between different types of trials. The following comparisons will examine differences in performance based on whether the same or different response is required in the current trial versus the previous trial, whether there is a special benefit for repetition trials in dual-task blocks, and whether performance is affected in dual-task blocks when only some aspect of the trial repeats. Although these comparisons shed light on the sources of mixing costs and the relationship between the tasks, none of the analyses reported in this section change the main findings of small or large dual-task costs reported in Experiments 1 – 14. Rather, they utilize additional comparisons afforded by the multiple block types and trial types in these experiments to delve deeper into the potential sources of these costs.

In particular, the fine-grained analyses will be used to examine the negative dual-task cost reported in Experiment 11. Although the presence of a negative dual-task cost is problematic based on the logic of the subtraction method used to motivate these comparisons, the evidence accumulated from the experiments presented here strongly suggests that dual-task scenarios fundamentally change participants' representation of the two tasks such that establishing a perfect single-task baseline for comparison may be impossible. As argued previously, single-task trials from the OR blocks seem to offer a slightly better comparison because the trials in these blocks keep the cognitive load constant; however, it is possible that for some of these task pairings, as in Experiment 11, switch costs contributed more heavily than load costs to overall RT in the OR blocks.

This would explain the negative dual-task cost observed with the coarse measure. The fine-grain analyses will be used to examine this possibility.

Overview of comparisons

In the results discussed so far and in previous IM-compatible studies, the bulk of the debate has focused on the experimental conditions necessary to dramatically reduce or eliminate dual-task costs. However, our findings reveal robust mixing costs in nearly every condition, even when there are no significant dual-task costs. As mentioned previously, mixing costs may have a variety of sources (Los, 1996). Interference could arise from the uncertainty associated with which task will appear on a given trial, or from the additional cognitive load caused by increasing the number of S-R pairs that must be maintained in working memory.

Three potential sources of interference will be examined in the following section. The first is the variability in the proportion of exact repetitions across blocks, the second is the interference due to switch costs and the third is the added strain of maintaining multiple task sets in working memory.

Exact Repetitions

Research has shown that trials which are exact repetitions of the previous trial may not be representative of the response selection processes taking place for the majority of the trials because everything is identical. RTs for exact repetitions are usually much faster than other types of trials (Pashler & Baylis, 1991). Somewhat surprisingly, the effect of exact repetitions on dual-task costs is not widely discussed in dual-task studies. As such, it is possible that some of the differences between blocks, particularly between the OR and single-task blocks, comes from the effect of exact repetitions. It could be that rather than being slowed by the requirements of the OR blocks or AND blocks, participants are faster in the single-task blocks because two-choice tasks make it so that half of the trials are exact repetitions. In the OR and the AND blocks, the increased number of S-R pairs make it so that only one quarter of all the trials are exact repetitions. This difference in the proportion of exact repetitions could be causing differences in overall RTs across blocks that are contributing to the coarse measures of mixing and dual-task costs. To check this, trials in the single-task blocks can be divided into alternate response trials and exact repetition trials. A significant difference between these two trial types would suggest that the proportion of exact repetitions may be speeding up overall RTs.

Switch Costs

At least one possible source of interference that may be contributing to the overall mixing costs arises from requiring participants to switch between tasks from trial to trial. Switch costs are the most likely to affect performance in the OR blocks; in AND blocks and single-task blocks participants always know which task, or tasks, they will perform on each trial. Switch costs are calculated by comparing trials from the OR blocks in which the current response was the opposite trial type (e.g., vocal) as the previous response (e.g., manual). This measure also takes into consideration how probable each type of trial is in a given block. In the OR blocks, both of these trial types – same task, alternate response and alternate task, alternate response – have a .25 probability of occurring, so because I intentionally did not include exact repetitions in this measure, this difference cannot be solely attributed to the variability in the overall probability of events.

Cognitive Load

Another important difference between single- and OR blocks that could affects performance is the fact that OR blocks require participants to maintain multiple S-R pairs in working memory. Typically, RTs increase as a direct result of having more S-R pairs to keep active. This is known as the Hick-Hyman effect (Hick, 1952; Hyman, 1953). To account for this, I will compare trials from the OR blocks in which the task is the same as it was on the previous trial but the alternate response is required to trials from the single-task blocks in which the alternate response is required. This measure takes into consideration the amount RT is affected by the strain of keeping two task sets active instead of one, but keeps constant the number of responses participants have to make on each trial. Again, this measure eliminates exact repetitions from both the OR trials and the single-task trials. So, in this comparison I am only looking at trials from the OR block in which the task repeated, but participants were required to make the alternate response, compared to single-task alternate trials.

Re-binding Costs

One of the main conclusions that can be drawn from Halvorson et al., (2012) and the findings from the PM 2x2 is that the relationship between the two tasks matters. One way to examine this relationship is to look at re-binding costs in the AND blocks. Re-binding costs arise when there is a partial re-activation of information from the last trial (for example, the AV task repeated) but the other task switched. Re-binding costs are one measure of the extent to which the two tasks influence each other on dual-task trials. If information about both tasks is included in the representation that is formed when a stimulus is bound to a particular response, performance will be slower when one of the tasks repeats and the other alternates compared to trials where both tasks stay the same or both tasks change. In other words, trials in which the response for one task changes and the other repeats will actually be slower than when both tasks change if the particular task pairing on a given trial influences response selection. If this is the case, the task that gets repeated might partially reactivate the last task it was paired with which would make it harder to select a different response on the current trial. If the combination of tasks does not matter, then it should not be any harder to have one of the tasks change and the other stay the same than it is for both tasks to change. No re-binding costs would suggest that the relationship between tasks does not matter and participants are not integrating the tasks in any way. If RTs are slowed when only one of the tasks changes and the other repeats compared to complete alternations, we can infer that response selection for each task is influenced by the concurrent task.

Stringent dual-task costs

To avoid including other types of interference in the dual-task costs, a very stringent way of calculating dual-task costs for the AV task is to look only at the difference between trials from AND blocks where both tasks alternate and AV trials from the OR block in which the task repeated, but the alternate response was required. Likewise for the VM task, dual-task costs can be calculated by subtracting RTs from VM trials in the OR blocks in which the task repeated but the alternate response was required from AND trials in which both tasks alternated. Although this approach prevents large switch costs in the OR blocks from masking a significant dual-task cost, it relies on the assumption that there is no switch costs on dual-task trials. However, this assumption might be too strong, since AND trials may contain a type of switch cost (see e.g., Lien &

Ruthruff, 2004). According to Lien and Ruthruff (2004), when the ensemble of tasks repeats, as the AV and VM tasks do on each trial in the AND blocks, the switch costs for the individual tasks are minimal. However, they found that there was still a switch cost associated when individual elements of a task changed on dual-task trials. This suggests that there may be a switch cost on the AND trials when both tasks alternate.

This measure also equates for the probability of each trial type across the blocks better than the coarse measure that included all trial types. The probability of this trial type (where the task repeats but the response alternates) is one fourth for both the AND and OR blocks. So, this measure provides an estimate of dual-task costs with an equally likely event probability for each trial used in the comparison. This measure also avoids including re-binding costs that could occur on some trials in the AND blocks.

Experiment 1 Fine-grained analyses

Figure 18 depicts the fine-grained analyses for Experiment 1, the arbitrary task pairing. In the top left hand corner (Figure 18), the difference between exact repetition and alternation trials in the single-task blocks is plotted for both tasks. In the AV task, the difference between alternations and repetitions was significant, $t(19)=2.96$, $p<.01$; in the VM task, the difference was not significant, $t<1$. This means that exact repetitions were performed significantly faster in the AV single-task blocks, but not for the VM blocks. In the AV task, trials in which everything was identical to the previous trial were significantly faster than trials which required the alternate response.

Table 3. The comparisons examined in the fine-grained analyses.

Fine-grained measure	**Trial types used for comparison**	**Benefit**
Exact Repetitions	Single response alternations – Single response repetitions	No switch costs
Switch Costs	OR task alternations – OR response alternations	No exact repetitions
Cognitive Load	OR response alternations – Single response alternations	No exact repetitions No task switches
Re-binding	AND both tasks alternate – AND one task repeats, one alternates	No exact repetitions
Stringent Dual-task	AND both tasks alternate – OR response alternations	No exact repetitions No task switches

Note: It is important to note that these measures are not entirely independent since some of the same trial types are used in multiple analyses.

Instead of showing a single measure of mixing costs, there are two types of interference plotted in the top right corner of Figure 18. The black bars represent switch costs, or the difference between trials in the OR blocks in which the task changed from the previous trial and trials in which the task stayed the same but the S-R pair alternated. This measure provides an estimate of how much participants are slowed by having to go from making a verbal response to a manual response, or vice versa. For the AV task, the switch costs were significant, $t(19)=4.54$, $p<.001$; the difference was not significant for the VM task, $t<1$. The gray bars in that graph represent the difference between OR trials in which the task stayed the same but the response alternated and single-task alternations.

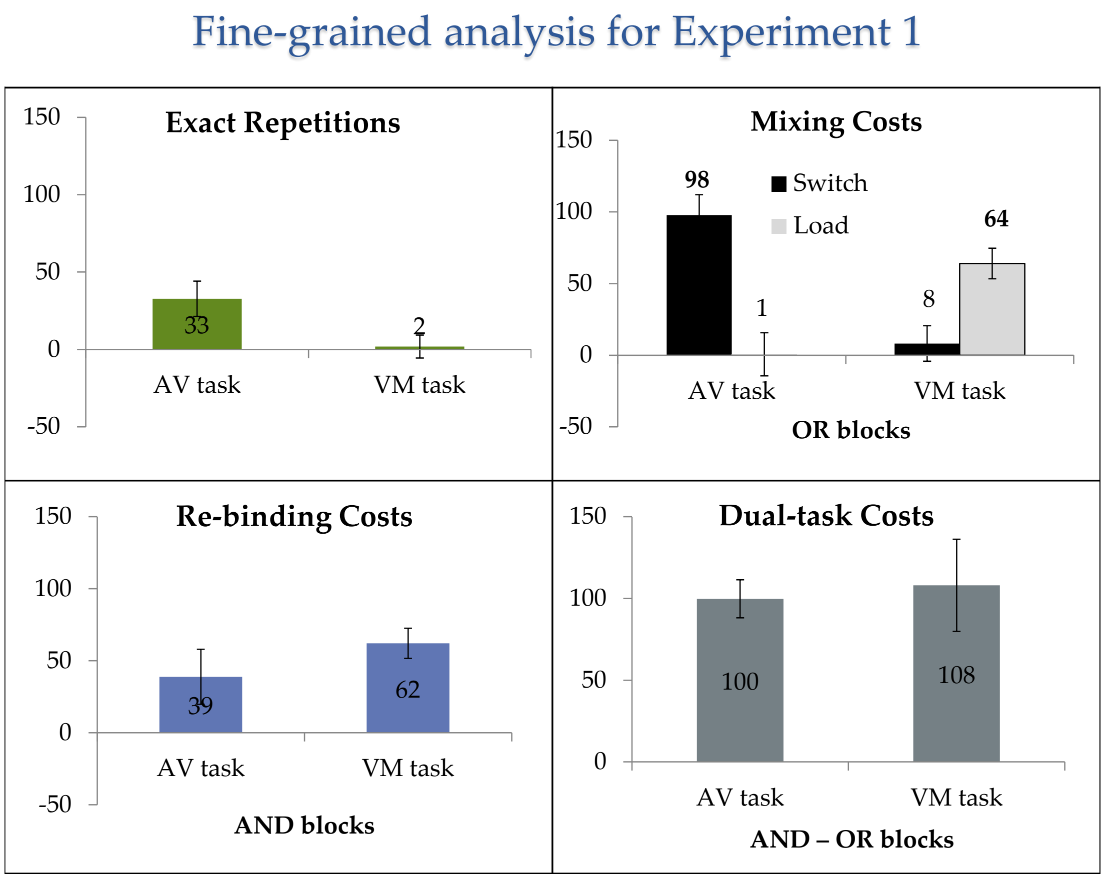


Figure 18. Four fine-grained measures of interference with an arbitrary-arbitrary task pairing. A bold number indicates a significant difference.

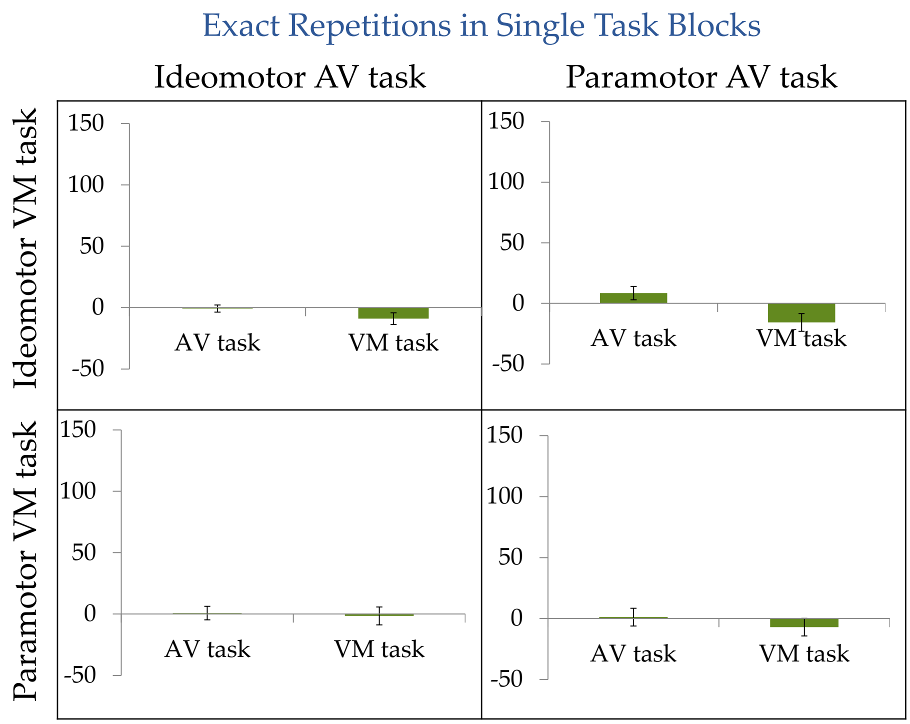
This measure reflects the amount to which the strain of maintaining two task sets in working memory affects RT even when only one response is made. For the AV task, this was not significant, t<1. For the VM task, there was significant effect of cognitive load, $t(19)=6.12$, $p<.001$. Taken together, the data from the OR blocks in the top right corner suggest that both switch costs and cognitive load affect RT in the OR blocks, although the switch costs seem to affect vocal responses and cognitive load affects manual responses.

The bottom left corner of Figure 18 depicts the re-binding costs for the AV and VM tasks in the AND blocks. For the AV task, the difference between trials in which the AV task repeated and the VM task alternated compared to trials in which both tasks alternated was significant, $t(19)=2.09$, $p<.05$; the difference between trials in which the VM task repeated and the AV task alternated and trials where both tasks alternated was also significant, $t(19)=6.12$, $p<.001$. This result shows how a partial re-activation on an AND trial can slow responding compared to a complete alternation; this can be taken as evidence against the notion that on dual-task trials, participants simply perform each choice RT task concurrently but completely independently. Instead, it seems that participants are binding the information from both tasks into the S-R representation for a given task.

The bottom right corner of Figure 18 depicts the stringent dual-task costs. These costs were significant for both the AV task, $t(19)=8.80$, $p<.001$, and the VM task, $t(19)=3.93$, $p<.001$. This pattern is consistent with the pattern of results if all trials are considered, which suggests that there is still a performance decrement when participants are required to make two responses at the same time as compared to one, even when different sources of interference are accounted for.

Exact Repetitions

In the IM-IM, PM-PM and IM-PM experiments, there was no benefit for exact repetitions for either the AV or the VM tasks, (see Figure 19, top), all *ts*<1. In the PM-IM experiment, there was no effect of repetition for the AV task, $t(19)=1.59$, $p=.13$, but there was a small negative effect in the VM task, $t(19)=2.78$, $p<.01$.



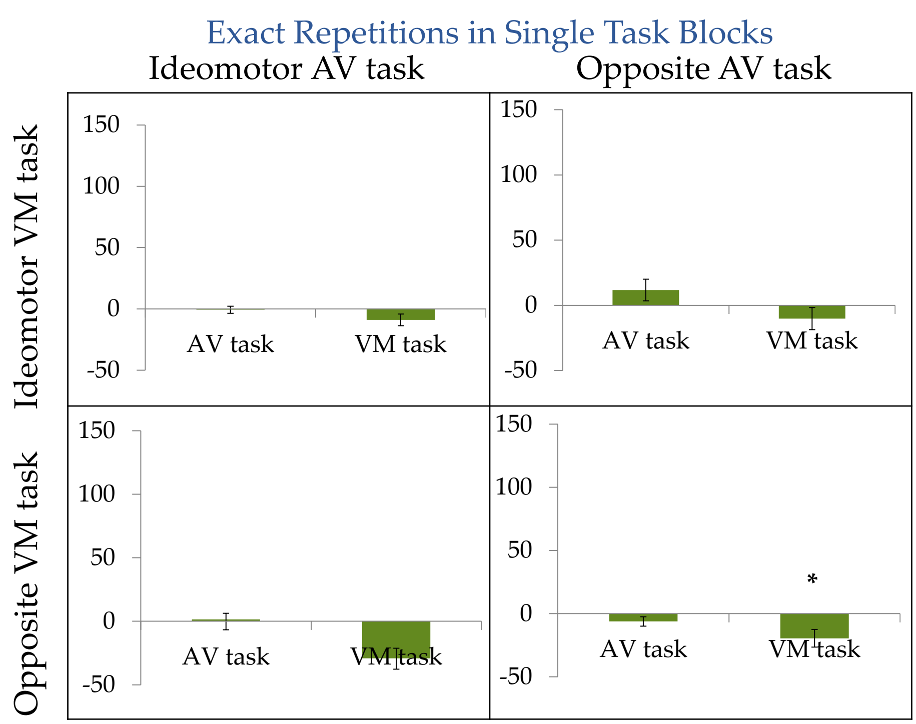


Figure 19. The difference between alternate response trials and exact repetition trials in the single-task blocks.
Top: PM 2x2
Bottom: OPP 2x2.

So, when the AV task was paramotor and the VM task was Ideomotor, participants were actually slightly faster on alternations than repetitions in the single-task VM blocks. This suggests that RTs are not significantly faster on exact repetitions than alternations for any of the experiments in the single task blocks.

For the OPP-OPP experiment (Figure 19, bottom, lower right quadrant), for the AV task, there was no difference between exact repetitions and alternations, $t(19)=1.72$, $p=.10$, and in the VM task there was actually a reverse effect; participants were 20 ms slower on repetition than alternation trials, $t(19)=2.86$, $p<.05$. On alternation trials, the previous response required a keypress from the finger that is depressed in the image on the present trial. So it is possible that this response-stimulus compatibility sped up RT on the current trial, however, participants still had to make the opposite response to the stimulus on that trial.

The pattern of results was the same for the IM-OPP experiment, (Figure 18, bottom, lower left quadrant). There was no effect of repetition for the AV task, $t<1$, and alternate responses were actually 29 ms faster than exact repetitions, $t(19)=3.75$, $p<.01$. For the OPP-IM experiment (Figure 18, bottom, top right quadrant), there was no difference between the AV task, $t(19)=1.53$, $p=.14$, or the VM task, $t<1$. The results for the trial type comparisons were the same as the IM-IM experiment as well; exact repetition trials did not produce significantly different RTs than alternations in either the AV task, $t(19)=1.46$, $p=.16$, or the VM task, $t(19)=1.22$, $p=.23$. It is interesting to note that while these comparisons are very similar to the IM-IM experiment, tasks in which participants had to follow the rule “do the opposite” for one or both tasks showed very different results from the Arbitrary-Arbitrary experiment mentioned earlier which showed a significant benefit for repetitions in the AV task.

Switch Costs

Switch costs were calculated for both tasks in all experiments. In the IM IM experiment (Figure 20, top, upper left quadrant), the switch costs were significant for both the AV (41 ms) and the VM tasks (24 ms), $t(19)=2.72$, $p<.05$ and $t(1,19)=4.54$, $p<.001$ respectively. For the PM PM experiment (Figure 19, top, lower right quadrant), switch costs were 99 ms for the AV task and 79 ms for the VM task, $t(19)=5.34$, $p<.001$ and $t(19)=4.41$, $p<.001$ respectively. For the IM PM experiment (Figure 20, top, lower left quadrant), switch costs were 36 ms for the AV task and 75 ms for the VM task, $t(19)=3.29$, $p<.01$ and $t(19)=4.75$, $p<.001$ respectively. Finally, the PM-IM experiment (Figure 20, top, upper right quadrant) showed the same pattern, with switch costs of 46 ms for the AV task and 17 ms for the VM task, $t(19)=3.69$, $p<.001$ and $t(19)=2.44$, $p<.05$ respectively.

These costs suggest that part of the mixing costs result from participants actually having to switch from performing one of the tasks on one trial to making a response to the other type of task on the next trial. So, for example, participants are slower on trials that require a manual response when the previous trial required a verbal response than when the current trial requires a manual response and the previous trial required the alternate manual response.

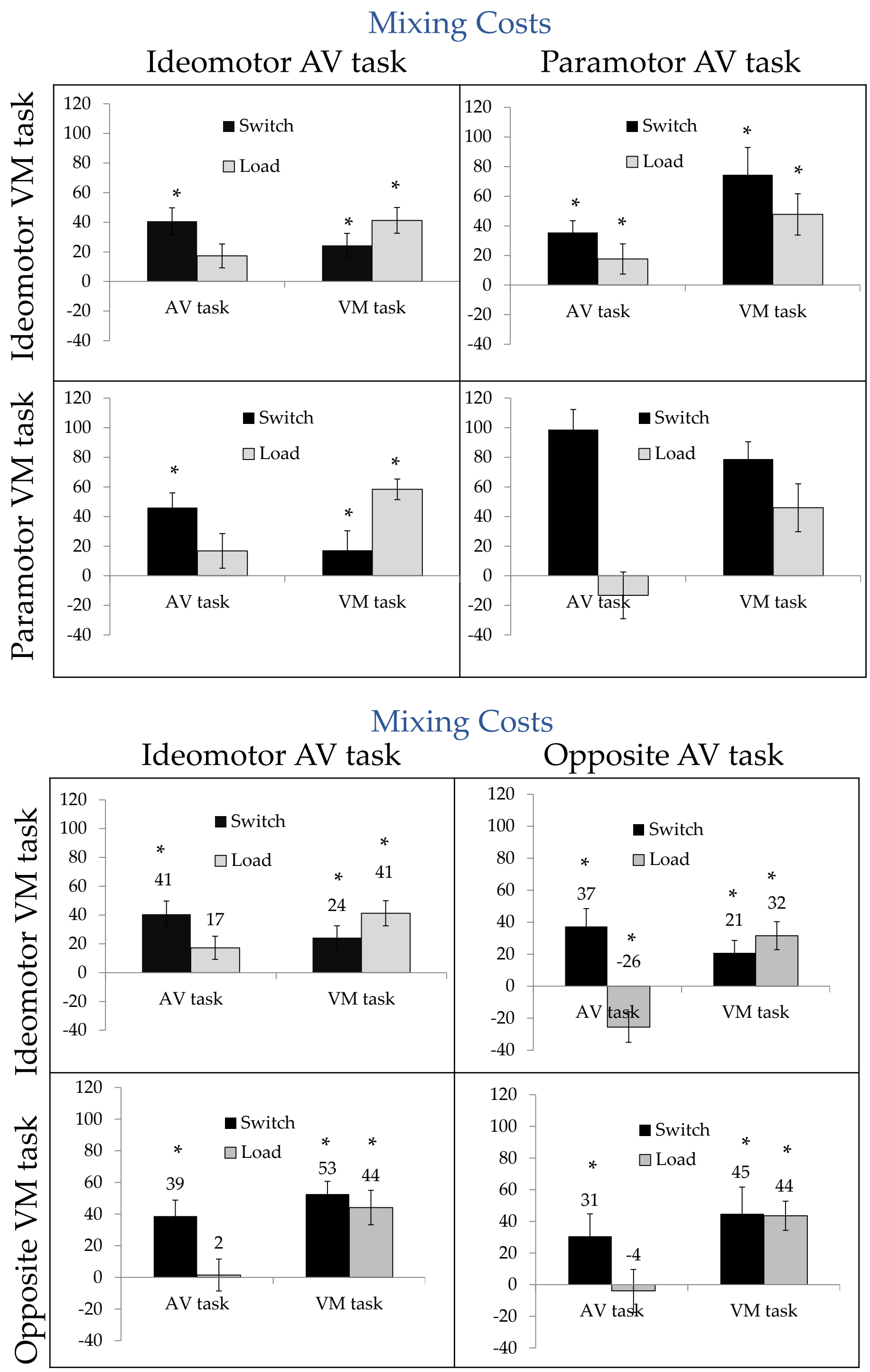


Figure 20. Switch costs and load costs for the AV and VM tasks.
Top: PM 2x2.
Bottom: OPP 2x2.

This measure also takes into consideration how probable each type of trial is in a given block. In the OR blocks, both of these trial types – same task, alternate response and alternate task, alternate response – have a .25 probability of occurring, so because I intentionally did not include exact repetitions in this measure, this difference cannot be solely attributed to the variability in the overall probability of events.

For the OPP OPP experiment (Figure 20, bottom, lower right quadrant), the switch costs were 37 ms for the AV task, $t(19)=3.83$, $p<.01$ and 24 ms for the VM task, $t(19)=3.15$, $p<.01$. Switch costs were also significant for the AV task in the IM-OPP experiment (Figure 20, bottom, lower left quadrant), $t(19)=4.26$, $p<.001$ and the VM task, $t(19)=2.17$, $p<.05$. Likewise for the OPP IM experiment (Figure 20, bottom, upper right quadrant), the AV switch costs were significant, $t(19)=4.22$ $p<.001$ as were the VM costs, $t(19)=4.66$, $p<.001$. These results indicate that a portion of the overall mixing costs reported earlier come from the strain of alternating between tasks from trial to trial.

Load Costs

The load costs were marginally significant for the AV task (17 ms) in the IM IM experiment (Figure 20, top, upper left quadrant) and significant for the VM task (41 ms), $t(19)=1.95$, $p=.07$ and $t(19)=5.22$, $p<.001$ respectively. In the PM IM experiment (Figure 20, top, upper right quadrant) in which the overall pattern of mixing and dual-task costs was very similar to the IM-IM experiment, the load cost was significant for both the AV (18 ms) and the VM (48 ms) tasks, $t(19)=2.28$, $p<.05$ and $t(19)=2.66$, $p<.05$ respectively. In the PM PM experiment (Figure 20, top, lower right quadrant), there was no effect of load in the AV task (-13 ms), $t<1$, but it was significant for the VM task (46 ms), *t*(19)=4.01, *p*<.001. Finally, in the PM IM experiment (Figure 20, top, lower left quadrant), in which there were large mixing and dual-task costs for both tasks, the load costs for the AV task (17 ms) were not significant, *t*(1,19)=1.74, *p*=.10, but they were significant for the VM task (58 ms), *t*(19)=4.56, *p*<.001.

In the OPP-OPP experiment (Figure 20, bottom, lower right quadrant) there was no effect of load on the AV task, *t*<1, and a significant effect for the VM task, *t*(19)=2.64, *p*<.05. In this experiment, the mixing costs for the AV task were mostly due to the uncertainty associated with not knowing which trial type to expect on the next trial. For the VM task, both switch costs and the strain of maintaining multiple tasks in working memory contributed to the overall mixing costs.

The pattern was similar for the OPP-IM experiment (Figure 20, bottom, upper right quadrant) except that the negative load cost for the AV task was significant, *t*(19)=2.36, *p*<.05. The load cost for the VM task was positive, suggesting participants were slowed by the added cognitive load of a second task set compared to pure, single-task blocks, *t*(19)=3.69, *p*<.01. The IM-OPP condition (Figure 20, bottom, lower left quadrant) showed a nearly identical pattern of results as the OPP-OPP experiment, with no significant effect of load for the AV task, *t*<1, and a significant effect for the VM task, *t*(19)=4.16, *p*<.001.

Summary

Switch costs were significant for both tasks in all four experiments, but the magnitude of the effect varied depending on the task pairings in the experiment. For example, larger switch costs were observed in the IM VM task when it was paired with the PM AV task than when it was paired with the IM AV task.

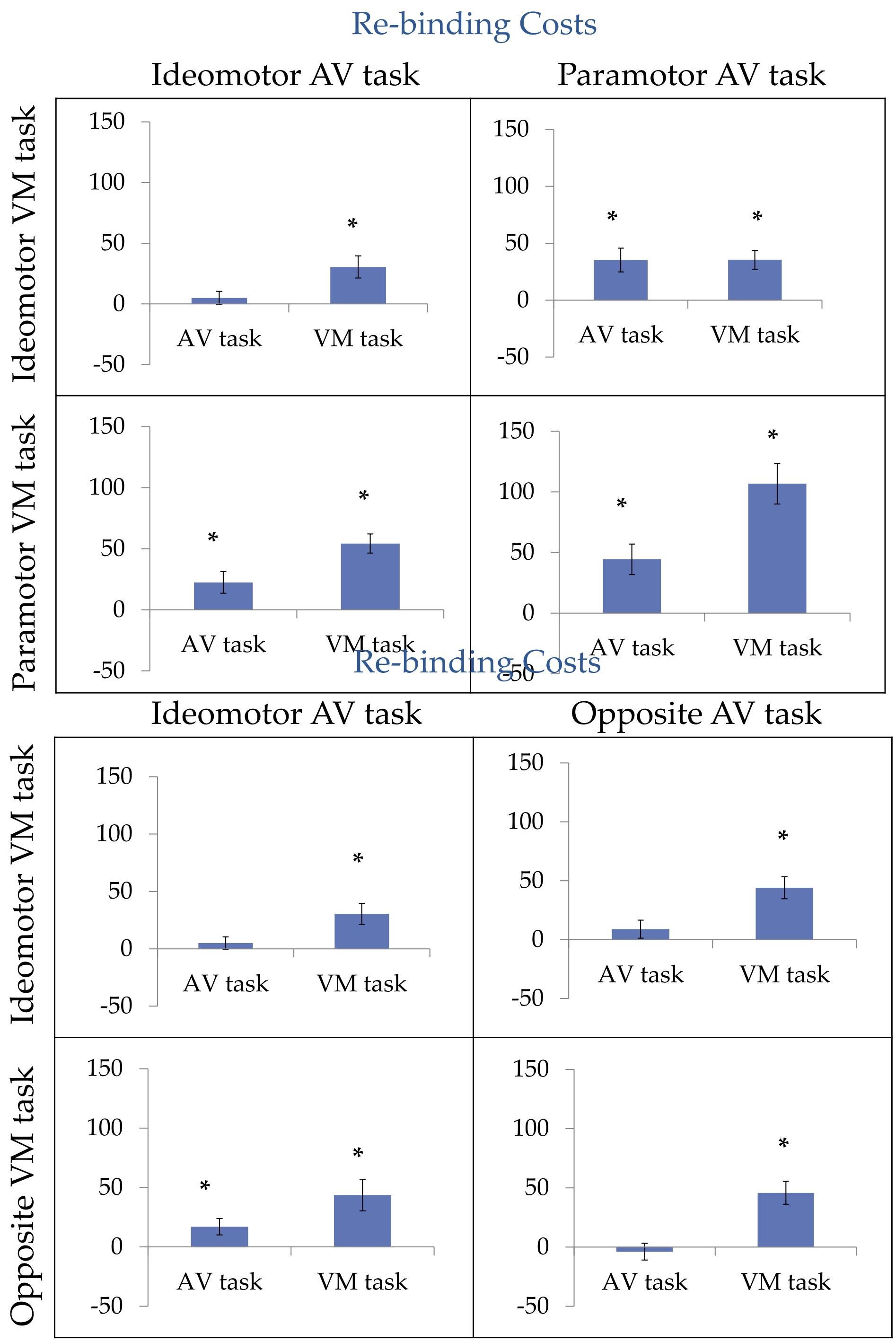


Figure 21. Re-binding costs for the AV and VM tasks.
Top: PM 2x2.
Bottom: OPP 2x2.

Unlike the switch costs, the magnitude of the effect of cognitive load was very similar regardless of which tasks were used.

Although it appears switch costs play a larger role in the AV mixing costs and cognitive load effects contribute more to mixing costs in the VM task, in some cases (like when the VM task was OPP) the mixing costs were essentially evenly divided between switch and load costs. Taken together, these results show a significant influence of both switch costs and mixing costs on performance. More importantly, they provide the first systematic analysis of contributing factors to mixing costs in dual-task experiments.

Re-binding Costs

To obtain a measure of re-binding costs for the AV task, RTs from trials in the AND blocks in which both tasks alternated were subtracted from trials in which the AV task repeated and the VM task alternated. For the VM task, it was the opposite; RTs from trials in which both tasks alternated were subtracted from trials in which the VM task repeated and the AV task alternated. In the PM 2x2 (Figure 20, top), significant re-binding costs were observed in the VM task for all experiments in the PM 2x2, all $ts>3.18$, $p<.001$. For the AV tasks in the PM 2x2, re-binding costs were not significant when both tasks were IM-compatible, $t<1$, but for the other three experiment, re-binding costs were significant for the AV task, all $ts>2.46$, $p<.001$.

Interestingly, re-binding costs were only significant for both tasks in the IM-OPP experiment (Figure 21, bottom, top right quadrant). For the AV task, there was a 17 ms cost, $t(19)=2.42$, $p<.05$, and a 44 ms cost in the VM task, $t(19)=3.12$, $p<.01$. So when the AV task was IM compatible and participants were required to select the opposite response of what was depicted in the VM task, the tasks influenced each other during response selection. In the OPP-IM experiment (Figure 21, bottom, upper right quadrant), there was no cost in the AV task, $t(19)=1.18$, $p=.24$, but the 44 ms cost in the VM task was significant, $t(19)=4.27$, $p<.001$. In the OPP-OPP experiment (Figure 21, bottom, upper right quadrant), the same pattern was observed with no cost in the AV task, $t<1$, and a cost of a very similar magnitude (46 ms) in the VM task, $t(19)=4.31$, $p<.001$.

Taken together, these results suggest that trials from the AND blocks in which the VM task repeats but the AV task alternates are slower than trials in which both tasks change. This is evidence against the notion that, for the VM task at least, responses are selected entirely independently of the other task on dual-task trials. This variability between trial types informs our understanding of how responses are selected on dual-task trials; perfect time-sharing was observed in all four experiments, but this analysis shows that the brain was not choosing two separate responses entirely independently of the information associated with the other task on dual-task trials.

The re-binding costs show that even when dual-task costs are not observed with a particular task pairing, the particular combination of S-R pairs selected on a given trial can leave a trace within response selection mechanisms as evidenced by the rebinding costs. This cost appears to be larger for experiments that showed significant dual-task costs, than for those that did not. This is evidence against the hypothesis that when perfect time-sharing is observed response selection is occurring independently for each of the tasks. Instead, these costs suggest that the process of response selection results in some linking of the two tasks.

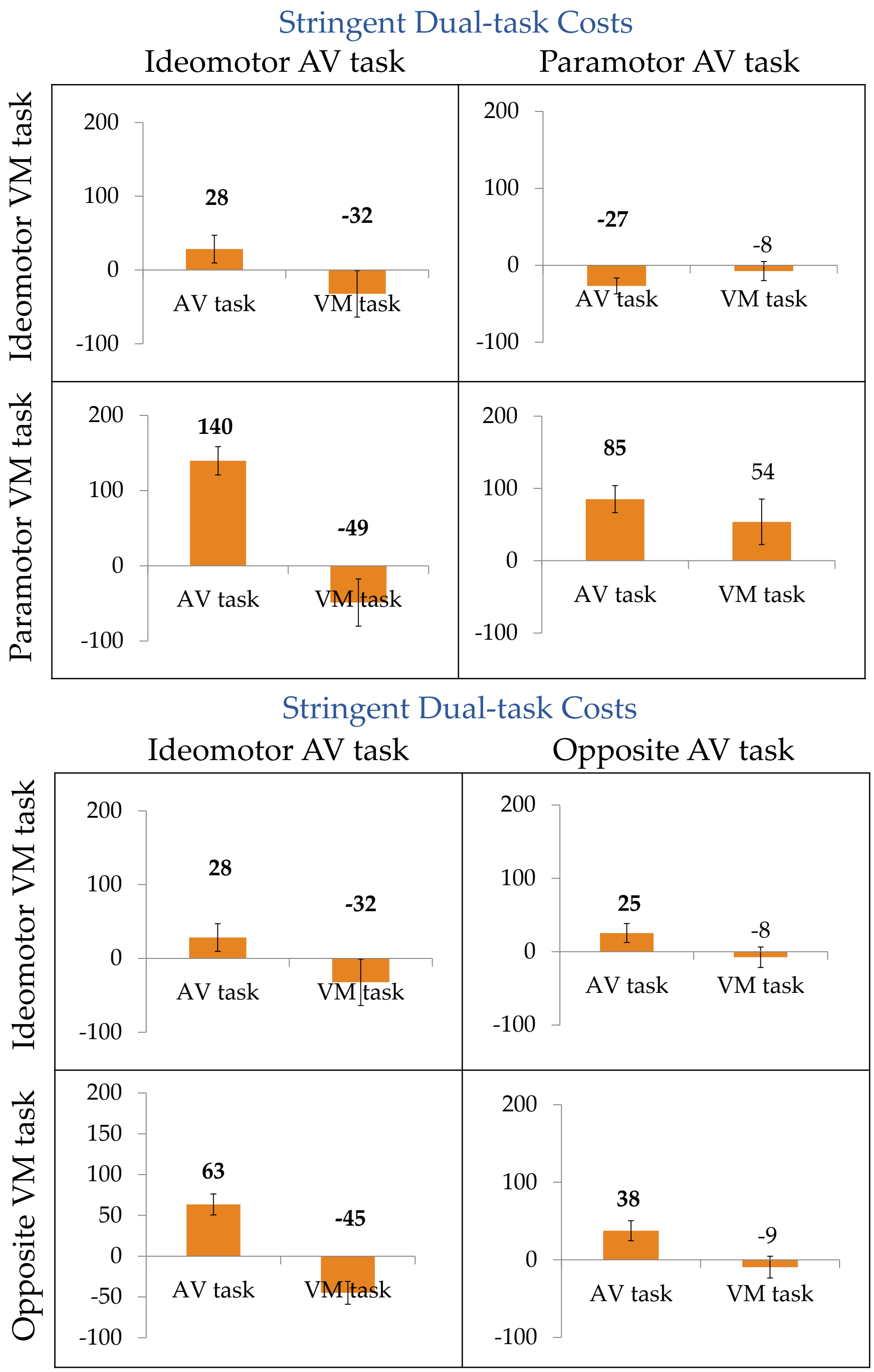


Figure 22. Stringent measure of dual-task costs for the AV and VM tasks.
Top: PM 2x2.
Bottom: OPP 2x2.

Stringent Dual-task Costs

With the stringent measure of dual-task costs, there was a relatively small (28 ms) dual-task cost for the AV task, $t(19)=2.52$, $p<.05$, and a negative cost (-32 ms) for the VM task, $t(19)=2.46$, $p<.05$ in the IM IM experiment (Figure 22, top, upper right quadrant). The sum of the overall costs for this experiment was -24 ms. The sum of the new costs, -4 ms, suggests that although the coarse analysis included all trial types, the overall pattern of results is consistent. It is interesting to note, however, that when the tasks are examined separately, the new measure reveals a significant cost for the AV task. In the AV task, the switch trials in the OR blocks were much slower than the other trial types included in the coarse measure (see Figure 22, top), so removing these trials caused the difference between the AND and the OR blocks to increase.

Although this measure provides an estimate of dual-task costs with an equally likely event probability for each trial used in the comparison, removing the switch costs from the OR blocks may have resulted in a slight overestimation of the dual-task costs. Alternatively, the difference between the AV and VM tasks could be reflecting a strategy adopted by participants on AND trials in which they prioritize the VM task, which typically takes longer to respond to, over the AV trials. Importantly, as in the previous analysis, the sum of the dual-task costs is essentially zero.

The pattern of results for the new measure of dual-task costs in the PM PM experiment (Figure 22, top, lower right quadrant), did not change dramatically in terms of the magnitude of the effect, although the VM costs are no longer significant. For the AV task, trials from the OR blocks were 85 ms faster than trials from the AND blocks, $t(19)=4.66$, $p<.001$, and 54 ms for the VM task, $t(19)=1.75$, $p=.09$. The magnitude of the sum of the costs is similar to the coarse analysis reported earlier. In this case, because of the significant re-binding costs on AND trials, using only complete alternations caused the dual-task costs to decrease. However, the sum of the costs for both tasks is still much greater than the sum of the costs with two IM-compatible tasks.

For the experiment with the PM AV task and the IM VM task, the pattern of results was very similar to the original estimates. The stringent analysis showed no significant dual-task costs ($t<1$) for the VM task and a significant negative dual-task cost (-27 ms) for the AV task $t(19)=2.65$, $p<.05$. Interestingly, both the AV and the VM task showed significant effects of switch costs and cognitive load in the OR analysis and significant re-binding costs, which suggests that these two tasks, although they lead to essentially perfect time-sharing (even with the most stringent analysis) are not processed independently on dual-task trials. The process of response selection appears to be influenced by the task pairings on each trial, which is not evident in the coarse measures of dual-task costs.

Finally, in the experiment with the IM AV task and the PM VM task, there were significant dual-task costs (140 ms) for the AV task, $t(19)=7.61$, $p<.001$, and significant negative costs (-49 ms) for the VM task, $t(19)=2.79$, $p<.001$. This pattern is similar to the original measures of dual-task costs, and was, perhaps, the most surprising result of all the experiments. Given the lack of costs observed with the PM AV task and the IM VM task, it is surprising that the reverse combination shows larger dual-task costs than two PM tasks.

When dual-task costs are calculated using only these trials for the OPP 2x2, in the IM OPP experiment (Figure 22, bottom, lower left quadrant), costs for the AV task are significant, $t(19)=3.26$, $p<.01$, and there is a negative cost for the VM task, $t(19)=3.58$, $p<.01$. The small, positive sum of these costs is similar to the slightly negative cost reported in the coarse analysis; the discrepancy can be accounted for by fact that the slower switch trials in the OR blocks were excluded. For the right column of this 2x2, the pattern was nearly identical. In the OPP IM experiment (Figure 22, bottom, upper right quadrant), there was a small positive cost for the AV task, $t(19)=2.42$, $p<.05$, and a non-significant difference in the VM task, $t<1$. For the OPP-OPP experiment (Figure 21, bottom, lower right quadrant), the AV costs were also significant, $t(19)=2.98$, $p<.01$, but the VM measure was not, $t<1$. For both of these experiments the AV costs were again likely influenced by removing the slower switch trials in the OR blocks. The sum of the costs for all experiments is still much smaller than that observed in the arbitrary-arbitrary experiment or the PM PM experiment. Even with this stringent measure, instructing participants to do the opposite did not result in large dual-task costs when both tasks used the opposite rule or when one task was opposite and the other was IM.

Experiment 11 Fine-grained analyses

Figure 23 depicts the fine-grained analyses for Experiment 11, in which the AV task was shadowing and the spatial VM task was used. In the top left hand corner (Figure 23) the difference between exact repetition and alternation trials in the single-task blocks is plotted for both tasks. The difference between trial types was not significant for the AV task, $t(25)=1.17$, $p=.25$, or the VM task, $t(25)=1.03$, $p=.31$. Thus, single task trials that were identical to the previous trial were not significantly faster than trials which required the alternate response.

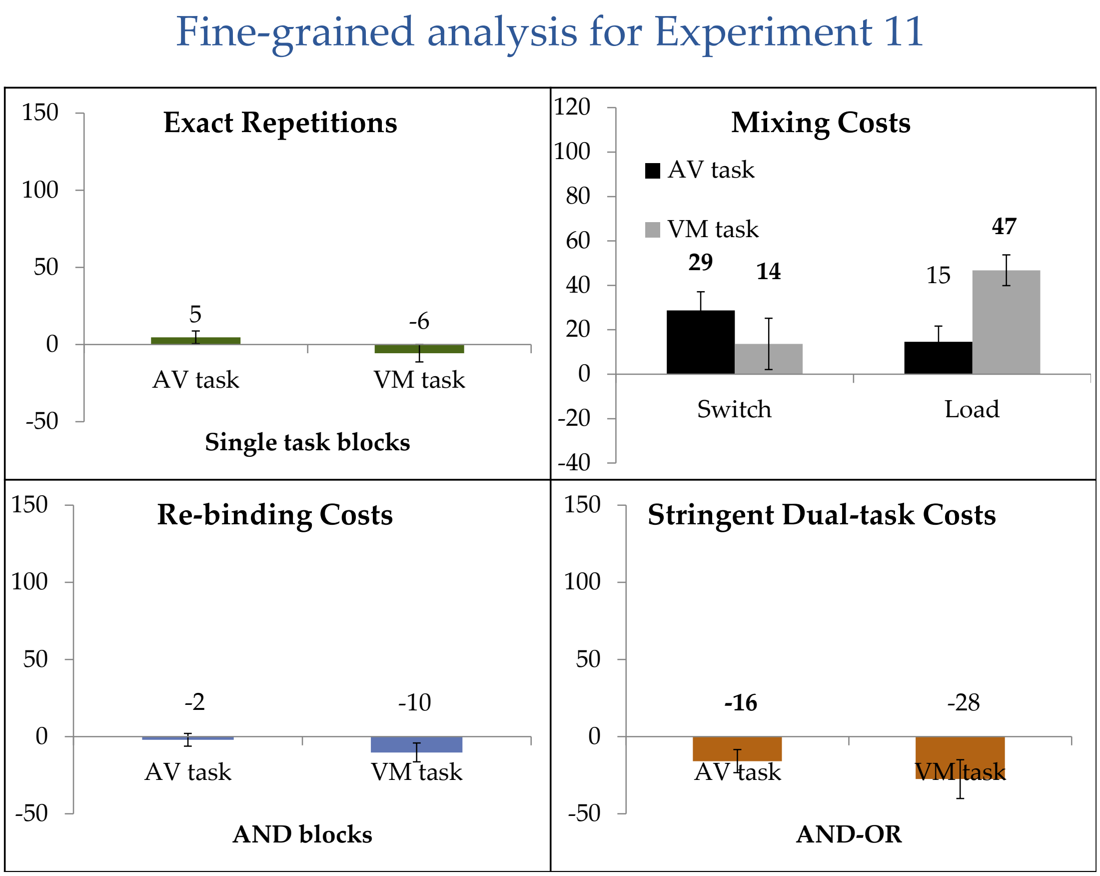


Figure 23. Four fine-grained measures of interference for Experiment 11.
A bold number indicates a significant difference.

In the top right corner of Figure 23 the mixing costs are broken down into switch and load costs. For the AV task, the switch costs (black bar, 29 ms) were significant, $t(25)=4.21$, $p<.001$; switch costs were also significant for the VM task (14 ms), $t(25)=2.06$, $p<.05$. The gray bars in the figure in the top right represent the difference between OR trials in which the task stayed the same but the response alternated and single-task alternations, or the costs associated with increasing cognitive load. For the AV task, this 15 ms difference was not significant, $t(25)=1.81$, $p=.08$. For the VM task, there was significant effect of cognitive load, *t*(25)=4.22, *p*<.001. Taken together, the data from the OR blocks in the top right corner suggest that both switch costs and cognitive load affect RT in the OR blocks, and similarly to several other task pairings, the switch costs were greater for the AV task and cognitive load influenced RTs more in the VM task.

The bottom left corner of Figure 23 depicts the re-binding costs, which were not significant for the AV or the VM task, *t*<1, and *t*(25)=1.83, *p*=.08, respectively. Unlike nearly every pairing in the OPP 2x2 and the PM 2x2, partial repetitions did not influence RT on the subsequent trial. In this case, it appears that having made one response to the VM task, for example, the left key, on a trial paired with a particular vocal response (e.g. "cat") did not cause a left key response on the subsequent trial to be slower if the vocal response was "dog." This suggests a greater amount of independence between the two tasks compared to the pairings that resulted in significant re-binding costs. Moreover, the lack of a re-binding cost could have contributed to the negative overall dual-task cost observed in this task pairing compared to other task pairings with minimal dual-task costs; there was no cost for the 50% of the AND trials in which only one element of the task pairing repeated.

The bottom right corner of Figure 23 shows the magnitude of the dual-task cost for each task using the most stringent measure. With this measure, the small negative difference in the AV task (-16 ms) was significant, *t*(25)=2.21, *p*<.05, but not for the VM task (-28 ms), *t*<1. The sum of these costs, -43 ms, was significant, *t*(25)=3.40, *p*<.01. Thus, eliminating exact repetitions from the measure of dual-task costs does not entirely explain the negative dual-task cost. However, taken together, the fine-grained analyses for Experiment 11 reveal interesting differences between this task pairing and the IM-IM and OPP-OPP pairings. Even though the coarse measures of dual-task costs were not significant in the latter two task pairings, the fine-grained analyses revealed significant effects of re-binding in addition to switch and load costs.

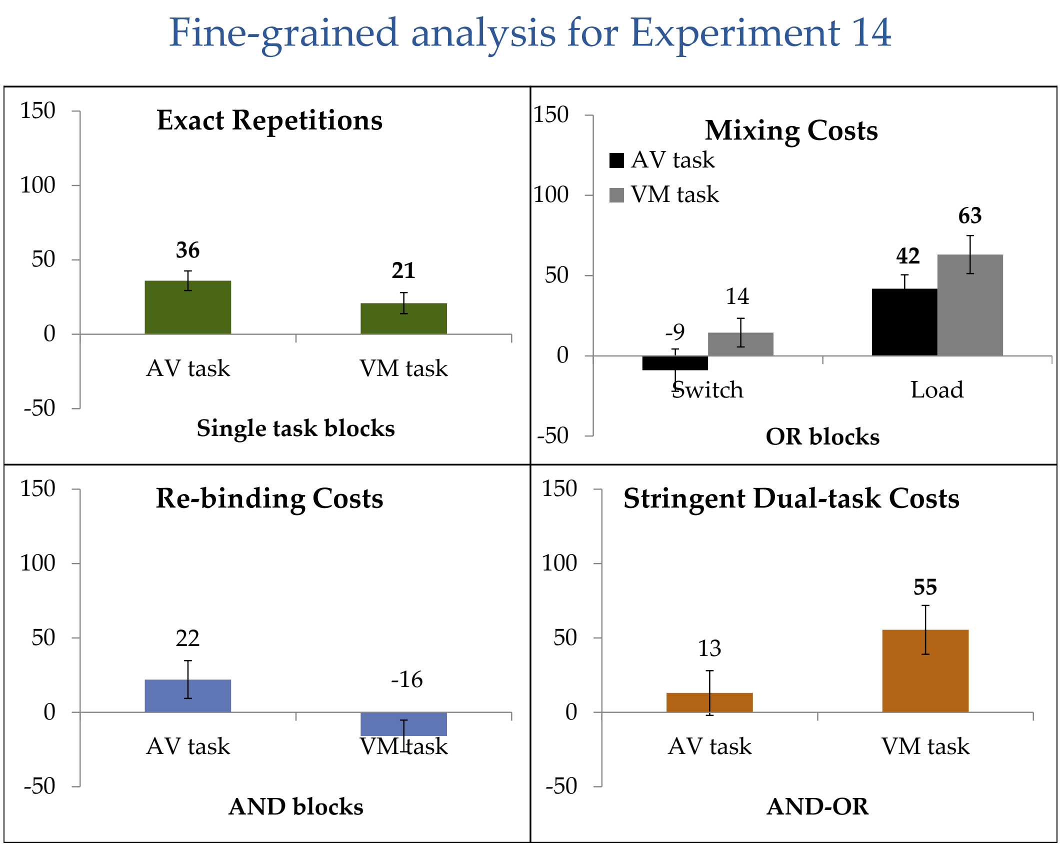


Figure 24. Four fine-grained measures of interference for Experiment 14.
A bold number indicates a significant difference.

Here, the pattern of switch and load costs was very similar compared to the IM-IM experiment, for example, but there was no evidence of re-binding costs. Perhaps for this task pairing, the strain of switching between tasks in the OR blocks was even greater than executing two responses when the level of uncertainty was kept constant in the AND blocks.

Experiment 14 Fine-grained analyses

Figure 24 depicts the fine-grained analyses for Experiment 14, in which mixed S-R pairs were used for both the AV and VM tasks. In the top left hand corner (Figure 24), the difference between exact repetition and alternation trials in the single-task blocks was significant for both the AV task (36 ms), $t(23)=5.62$, $p<.001$, and the VM task (21 ms), $t(23)=3.03$, $p<.01$. In this experiment, in the single task blocks, trials that were identical to the previous trial were significantly faster than trials which required the alternate response. Because these task sets used mixed S-R pairs, alternation trials consisted of a different type of stimulus; for the VM task, one was an image of a hand and the other was a colored square, and for the VM task, one was a tone and the other was a word. Increasing the differences between the stimuli for each task could have increased the benefit for exact repetitions compared to task sets with more homogenous stimulus sets.

In the top right corner of Figure 24 the mixing costs are broken down into switch and load costs. For the AV task, the switch costs (black bar, -9 ms) were not significant, $t(23)=1.06$, $p=.30$; switch costs were also not significant for the VM task (14 ms), $t(23)=1.25$, $p=.22$. The load costs (gray bars, top right, Figure 24) were significant for both the AV task (42 ms), $t(23)=3.24$, $p<.01$ and for the VM task, $t(23)=7.21$, $p<.001$. These measures suggest that the increased cognitive load associated with maintaining multiple task sets contributed to the overall mixing costs reported earlier more than switching between tasks. Given that the measure of cognitive load uses the alternation trials in the single task blocks, which were significantly slower than the repetition trials, it is not likely that the magnitude of the overall mixing costs was exaggerated by the benefit of the repetition trials. For this task pairing, maintaining both task sets, which consisted of unrelated stimulus and response sets, significantly slowed RT.

The bottom left corner of Figure 24 depicts the re-binding costs, which were not significant for the AV task (22 ms), $t(23)=1.76$, $p=.09$, or the VM task (-16 ms), $t(23)=1.50$, $p=.15$. Unlike the OPP 2x2 and the PM 2x2, but similarly to Experiment 11, partial repetitions did not influence RT on the subsequent trial in the AND blocks. Once again, having made one response to the VM task, for example, the left key, on a trial paired with a particular vocal response (e.g. “cat”) did not cause a left key response on the subsequent trial to be slower if the vocal response was “dog.” As in Experiment 11, it is possible that the decreased similarity within the stimulus sets allowed for a greater amount of independence between the two tasks on dual-task trials.

The bottom right corner of Figure 24 shows the magnitude of the dual-task cost for each task using the most stringent measure. For the AV task, the cost (13 ms) was not significant, $t<1$, but it was significant for the VM task (55 ms), $t(23)=3.41$, $p<.01$. As in the other experiments, the sum of these costs reflects a similar pattern of results as the sum of the dual-task costs reported earlier.

Summary

Taken together, the fine-grained analyses offer three important additional conclusions about the mixing and dual-task costs in the experiments reported here. First, robust mixing costs were observed in every experiment; these analyses show that the mixing costs can attributed to at least two distinct sources of interference. Comparing trials from the OR blocks in which the trial type changed (e.g. required a vocal response when the previous trial required a manual response) to trials from the OR block in which the trial type stayed the same (e.g. the current trial required a vocal response as did the previous trial) gives a measure of costs associated with switching between the two tasks. Although switch costs accounted for more of the overall mixing costs for the AV task, in general, switching between the two tasks slows response time even when only one response is required.

Comparing trials from the OR block in which the trial type stayed the same (but the response alternated) to trials from the single task blocks in which the response alternated provides a measure of the effects of increasing cognitive load even when only one response is required and independently of switch costs. Although load costs often accounted for more of the overall mixing costs for the VM task, this measures shows that the strain associated with maintaining multiple task sets slows response time even when only one response is required and the current trial uses the same set of S-R pairs as the previous trial.

The second main conclusion is that the fine-grained analyses reveal differences between trial types in AND blocks for some of the task pairings. In some cases, two tasks which do not show evidence of overall dual-task costs show small differences in the magnitude of dual-task costs based on the difference in task pairings compared to the previous trial (this measure is referred to as the re-binding costs). Although several instances of dual-task performance resulted in minimal overall interference, re-binding costs suggest that even in these cases, the two tasks are not being processed entirely independently and that the *task pairings* matter. This suggests that theories in which the tasks are thought to be processed entirely independently or simply bypass response selection cannot account for these results. However, Experiments 11 and 14 showed a different pattern of results from the OPP 2x2 and PM 2x2. In these experiments, there was little evidence that partial repetitions slowed RTs in the AND blocks. Interestingly, the presence or absence of significant re-binding costs does not correlate with the presence or absence of dual-task costs. In the experiments in which there were no re-binding costs, one of them (Experiment 11) actually resulted in a negative dual-task cost, and the other (Experiment 14) resulted in significant overall dual-task costs. These differences warrant further investigation into the extent to which two tasks appear to be processed independently during dual-task trials, regardless of the magnitude of the overall dual-task costs.

Finally, the fine-grained analyses showed that even the most stringent measure of dual-task interference (exact repetitions and task switch trials were removed) did not show evidence of large dual-task costs. For all experiments, the overall patterns of results when compared to coarse measures of dual-task interference were very similar. This suggests that the lack of dual-task costs observed in these experiments is not purely the result of artifacts of the design, like certain trial types leading to very fast RTs (i.e. exact repetitions in the AND blocks) or certain trial types significantly slowing single task RTs used as a baseline (i.e. switch trials in the OR blocks). The rest of the general conclusions will be taken up in Chapter 8.

CHAPTER VII

FINAL SUMMARY

Collectively, the results reported here make several novel and important contributions that advance our understanding of the sources of dual-task costs. Before discussing the theoretical and practical implications of these findings, it is important to clarify what is meant by the term task. Although there are many definitions of tasks in both real world and laboratory settings, for the remainder of this discussion a task will be operationally defined as the combination of a set of stimuli, responses, and the pre-determined correct mappings. So, for example, the words “cat” and “dog” mapped to the vocal responses “cat” and “dog” constitute the IM AV task. Or, more generally, a task consists of the necessary input and outputs as well as the rules governing the relationships between them. Although there are many other possible definitions of a task, the following discussion will refer specifically to situations in which there is a correct response that must be selected based on a specific stimulus. In the following discussion coordinating multiple tasks will refer to these specific scenarios, in which there is a pre-determined S-R mapping, and may not directly apply to coordinating other types of motor tasks (for example, walking and chewing gum).

In the dual-task situations presented here, the task pairing is determined by the *combined* representation of the S-R pairs for the AV and VM tasks. First, and perhaps most importantly, it is clear that the magnitude of the dual-task costs depends critically on the collective S-R sets that make up the task pairing. Put differently, dual-task scenarios require participants to consider the S-R pairs for both tasks, which changes the representation of those tasks compared to situations in which each task is performed separately. When humans engage in multiple tasks at the same time, they are not just doing one task plus a second task; rather, dual-task scenarios change participants' conceptualization of the tasks to include the S-R pairs for both tasks even when only one task is being performed. Often, this leads to performance impairments for both tasks. But, this does not mean that there are zero situations in which two tasks can be performed simultaneously without slowing response times. Previous claims of structural limitations preventing simultaneous performance were largely based on dual-task paradigms that have been shown to lead to significant dual-task costs even if the two tasks can be performed simultaneously under difference circumstances (see e.g. Halvorson et al., 2012). These findings represent several novel instances of task pairings in which little to no dual-task costs were observed when the increased cognitive load associated with maintaining multiple task sets was accounted for and the tasks were always presented simultaneously on dual-task trials.

Mixing Costs

Part of the original research question was to examine possible sources of interference that may arise from different aspects of response selection. Response selection includes both maintaining the information required to carry out each task successfully but also selecting the appropriate action necessary to execute both responses. In the example of driving and talking on a cell phone, these costs are more or less equivalent to things like knowing traffic laws and the content of the conversation, and coordinating the foot and hand positions required to operate the automobile and the mouth and throat positions necessary for speaking, respectively. Including two measures of single task performance (single and OR conditions) in every experiment showed that the first source, increased cognitive load, causes significant performance impairment in every experiment. Significant mixing costs in all the experiments suggest that this type of interference consistently and robustly contributes to impairments associated with dual-task performance, even with task pairings that do not lead to large dual-task costs.

Another component of dual-task performance has to do with the amount of time it takes to do perform each stage (e.g. stimulus encoding, response selection, response execution) for each task. Some researchers have suggested that when the duration of the response selection stage is sufficiently short, dual-task costs can be avoided provided the two response selection stages do not overlap (e.g. Anderson et al., 1997). If the tasks take different amounts of time to complete overall, this can occur without requiring participants to strategically delay response selection for one task until the other is complete. Instead, it could be that only the encoding and response execution stages overlap and the response selection stages can happen serially without slowing RT. One way this question can be addressed is by examining the overall RTs across experiments to see if dual-task costs are consistently present with slow RTs and absent with fast RTs. This method is only appropriate when the manipulations across experiments are assumed to affect the response selection stage rather than the encoding or response execution stages, which can presumably happen in parallel.

The Opposite 2x2 provided the optimal scenario for checking whether response latencies are correlated with dual-task costs because all the stimuli and responses were identical for all four experiments. So changes in overall RT cannot be explained by suggesting that some stimuli were more difficult to encode than others or some responses took longer to perform. In these experiments, the Opposite rule slowed participants down significantly in both the AV and VM task in the OPP-OPP condition; presumably, asking participants to choose the alternate response from the pairing lengthened the response selection stage. The OPP VM task also slowed RTs compared to the IM VM task when it was paired with IM VM task. However, dual-task costs were not significant in any of the four conditions. These results suggest that very short response selection latencies cannot account for all cases of perfect time-sharing in dual-task performance (Anderson et al., 1997). In other words, dual-task costs are not perfectly correlated with increases in task difficulty or overall RT. Instead, the particular task pairing creates a new conceptualization of the tasks that includes a combined representation of both task sets, which results in multiple, distinct sources of interference.

Novel task pairings

In general, attempting to coordinate multiple tasks in which specific responses must be selected for a given stimulus at the same time leads to significant performance impairments. Previous studies of this type of dual-task performance in the lab have, to date, almost always resulted in significant dual-task costs. Perhaps somewhat surprisingly, many of the task pairings used in the paradigm developed in Halvorson et al. (2012) and discussed here showed minimal performance impairment for making two responses at the same time compared to a single response. These experiments used a paradigm that allowed for multiple measures of single task performance and encouraged simultaneous responding. Using OR trials a baseline for single task performance and simultaneous onset of the stimuli in the AND blocks provided the optimal scenario for minimizing dual-task costs with certain task pairings. Namely, situations with two simple 2-choice tasks in which the input and output modalities as well as the central codes are distinct resulted in small, non-significant dual-task costs. Although this criteria may sound specific, this set of experiments contains a significant amount of variability in the types of tasks that have resulted in minimal dual-task costs, and the subtle manipulations to the stimuli and mappings allowed for close examination of the factors that lead to dramatic changes in the magnitude of the costs. Identifying these factors allows for reconsideration of potential theories of response selection based on the predictions they make about dual-task costs. The following section will discuss the four hypotheses tested with these experiments and how the findings constrain the theories of response selection described in Chapter 1.

Theories of response selection revisited

Chapter 1 outlined several popular models of response selection that make different predictions about when dual-task costs should be observed. Experiments 3 through 6 tested the automatic activation hypothesis. This hypothesis predicts minimal dual-task interference when the relationship between the stimuli and responses is so highly compatible that the correct response is directly activated by the stimulus. Some theories of automatic activation postulate a two-part response selection stage in which one of the components can never be performed simultaneously, such that findings of small dual-task costs can be reconciled with bottleneck theories of response selection (see e.g. Kornblum et al., 1990; Lien et al., 2002). Under this framework, dual-task costs are eliminated when extreme levels of compatibility allow for automatic activation of the response simply by identifying the stimulus. This explanation can only account for the findings of minimal dual-task costs with two IM tasks. In the case of two opposite tasks, it is not possible that the same stimulus (e.g. the word “cat”) automatically activated the response “cat” in the IM-IM experiment and also the word “dog” in the OPP-OPP experiment. Even if the high amount of conceptual overlap between “cat” and “dog,” when the words “red” and “green” were mapped to the responses “cat” and “dog” in the PM IM experiment (Experiment 8) there was no evidence of dual-task interference. The relationship between these two colors and the responses “cat” and “dog” was arbitrarily created for the experiment, and it seems unlikely that there would be a direct route between hearing the word “red” for example, and saying the word “cat” in the absence of a great deal of practice.

Thus an automatic activation account is certainly not the most parsimonious for explaining the range of mappings and magnitudes of dual-task costs observed here. If some animals names are so highly related that hearing one automatically activates the other (e.g. “dog” and “cat”), then which animal names are not activated by hearing “dog”? Moreover, the automatic activation hypothesis struggles to account for the nuances of the findings based on the relationship between the two tasks. According to this account, the S-R pairs for one task should not necessarily influence performance in the other task. A better explanation for the findings from this set of experiments should explain why performance in the exact same task changes when paired with a different task.

The task coherence hypothesis was based almost exclusively on the relationship between the tasks. The task coherence hypothesis is perhaps most amenable to strategic models of response selection like the computational model of executive functioning known as EPIC (Meyer & Kieras, 1997). EPIC uses production rules to regulate the transmission of information throughout the brain and coordinate various aspects of response selection. According to this type of model, different scheduling strategies can be adopted during dual-task performance including interleaved scheduling, which allows for highly efficient performance of two tasks simultaneously. If the similarity between the rules for the S-R mappings for each task in the IM-IM and OPP-OPP experiments allowed for interleaved scheduling without practice, such a model of response selection would have been supported by the findings from Experiments 2 and 3. However, Experiments 4 through 6 showed a strikingly similar pattern of results without sharing a rule and without practice. There is no good reason to assume that a strategic model based on production rules like EPIC could switch to interleaved scheduling without practice for one opposite task and one IM task but not for one arbitrary task and one IM task. Thus, the findings from the OPP 2x2 ruled out both the automatic activation and the task coherence hypotheses and provide evidence against bottleneck models and strategic models of response selection based on production rules.

The two remaining models of response selection discussed previously, resource models and crosstalk models, share many of the same underlying assumptions and make predictions about dual-task costs based on the relationship between the two tasks. According to resource models, different tasks may require the use of distinct pools of cognitive resources, but when two tasks require the use of the same pool simultaneously, dual-task costs will be observed. Some resource models also incorporate the concept of crosstalk; crosstalk is defined as conflict that occurs when some aspect of one of the tasks influences or affects a variable that is necessary for performing the other task. According to these accounts, the IM compatible tasks required distinct pools of resources for processing, and did not contain crosstalk between any of the components of the two tasks.

This account can also accommodate the findings of the OPP 2x2, since the exact same elements were included in the stimulus and response sets.

In an effort to determine whether other tasks which used the same stimulus and response modalities but did not have highly compatible mappings could avoid dual-task costs, Experiments 7 through 10 tested the task set confusion hypothesis. This hypothesis makes many of the same predictions as resources models and theories of crosstalk. According to this hypothesis, when the stimulus set for one task is strongly related to the response set for the same task and is *not* related to the response set for the other task, dual-task costs will be eliminated. In this case, the relationship between the stimulus and response set within a task and the separability between the two tasks would result in processing each of the tasks in distinct pools. However, the results of the PM 2x2 were not consistent with these predictions. As discussed previously, it is possible that a better paramotor task pairing could have led to more efficient dual-task performance. The introduction of verbal labels to the PM VM task and the complex hand stimuli could have introduced crosstalk between the two tasks or made it so that the two tasks required the same pool of resources.

So again, although such an explanation cannot be ruled out, the PM 2x2 showed that at the very least, the images of hands in the IM experiments could not account for the elimination of dual-task costs in Experiments 1-10. Rather than pursuing a more ideal paramotor task, Experiment 11 used a spatial VM task with colored circles to test a new hypothesis, the CCC hypothesis. According to the CCC hypothesis, the magnitude of the dual-task costs depends on the central code necessary for binding the stimulus to the response. When one of the tasks requires a spatial central code and the other verbal, then dual-task costs can be eliminated. Experiment 11 showed that an AV shadowing task and a purely spatial VM task, which did not use the same central codes, could be performed simultaneously without costs. Thus, the CCC hypothesis used the term crosstalk to describe the source of interference in tasks that show dual-task costs when both tasks required the use of the same central code during the binding process.

The term central code was adopted from Wickens's (1983) resource theory of response selection. Although the inclusion of a central code and the description of the tasks as containing S-C-R pairings resemble a three part stage model of response selection, it is important to clarify that central codes are not the same as a central stage. Rather than suggesting that response selection consists of three distinct stages that must be completed serially, the inclusion of a central code is necessary to explain how the stimuli are bound to the responses. The central code is an additional component of the S-R pairs that make up the task set. When the task is being performed, the central code is activated in addition to the stimulus and response.

To this end, the findings from Experiment 14 show that even if the current trial consists of S-R pairs that previously resulted in no dual-task interference, significant dual-task costs will be observed if *any* of the S-R pairs in the two tasks require the same central code for binding the stimulus to the response. In this experiment, large dual-task costs were observed for all trials regardless of the S-R pairs used on individual trials. Comparisons across trial types showed no difference in overall RT or the magnitude of the dual-task costs. This suggests that the overarching task representation on dual-task trials includes all the components of the S-R pairs for both tasks. Presumably, if response selection occurred in a serial, discrete stage manner, then the central code for an S-R pair that was not necessary for the current trial would not lead to interference. Thus, the findings from these experiments suggest that dual-task situations create a combined representation of the two task sets that is actively maintained in its entirety throughout the experiment.

Relationship between tasks

The importance of the relationship between the tasks for determining the magnitude of the dual-task costs cannot be overstated. Several experiments showed that the exact same AV or VM task (or even S-R pair) that had previously shown no dual-task interference, for example, resulted in large dual-task costs when paired with a different task. According to the CCC hypothesis, the presence of dual-task costs depends primarily on whether there is crosstalk between the central codes necessary for binding the stimuli to the responses. However, the findings from Experiment 14 suggest that even if the central codes necessary for binding the stimulus to the response are distinct for the two tasks on a given trial, dual-task interference will arise if any of the S-R pairs for each task share a central code. This pattern of results suggests that dual-task costs are not determined by the relationship between components of specific S-R pairs; rather, the amount of dual-task interference depends on whether the two tasks use entirely distinct sets of resources.

Referring to the tasks as using distinct sets of resources as opposed to not containing crosstalk represents a small departure from the original description of the CCC hypothesis. Although using the term crosstalk avoids many of the problems with resource models described previously, in which the independence of resource pools cannot be verified by measures other than the presence or absence of dual-task costs, the relationship between the central codes for all the S-R pairs in Experiment 14 is difficult to describe in terms of crosstalk. If the source of the interference was exclusively crosstalk, that would imply that if the binding process for one of the tasks, say the AV task, on a given trial requires a verbal central code, that code affects processing on the concurrent task even if the S-R pair for the VM task on that trial does not require a verbal code but the inactive S-R pair does (e.g. the red square mapped to the keypress response). Thus, the findings from Experiment 14 suggest a framework that is more similar to a resource theory of response selection in which both tasks must be *entirely* processed in distinct pools.

Although resource models of response selection often face the criticism that resources are only defined post-hoc when interference is not observed, the critical insight offered by this set of experiments is that the two types of central codes (verbal and spatial) can be used to establish at least two distinct domain-specific resources pools. Although establishing a clear understanding of domain-specific resource pools has been problematic for theories of response selection, this concept has been extensively investigated in the working memory (WM) literature.

One such model of WM, first developed by Baddeley (1986), includes a domain general central executive in charge of coordinating the contents of various slave systems that exclusively store and process specific types of information. This model was designed to explain effects of capacity limitations in WM tasks that depend critically on the type of stored information. Baddeley & Logie (1999) originally proposed two distinct domain-specific slave systems, the visuospatial sketchpad and the phonological loop. These two systems correspond to specific types of sensory information: the phonological loop briefly holds information in a speech-based form and has a subvocal articulatory rehearsal process, and the visuospatial sketchpad is used to temporarily store and manipulate visual and spatial information.

There is a great deal of evidence from the WM literature that the capacity limits for each of these subsystems are not affected by the concurrent activation or rehearsal of information that can be exclusively processed in the other. For example, Cocchinie, Logie, Della Sala, MacPherson, & Baddeley (2002) paired different types of verbal or visual WM tasks (e.g. remembering lists of digits versus the layout of a checkerboard pattern of black and white squares) with various suppression tasks (e.g. perceptual, motor, or articulatory suppression). They showed that articulatory suppression tasks, for example, interfered with the verbal WM memory task but had little effect on the verbal task.

The findings from these experiments allow for relatively novel connections between the dual-task literature and domain-specific models of WM. With a few exceptions, (e.g. Hazeltine & Wifall, 2011), the relationship between such models of WM responsible for online task processing and coordination and the locus of dual-task interference has been relatively ignored. Hazeltine & Wifall (2011) showed different patterns of dual-task interference depending on the modality of the response in a choice-RT task, even when the modality of the stimulus was kept constant. For example, when the choice-RT task consisted of categorizing visually presented words as either “bugs” “food” or “trees” with a vocal response significantly reduced capacity for maintaining a sequence of tones. When the same choice-RT task was paired with a spatial WM task that consisted of remembering sequences of spatial locations, there was significantly less impairment. Critically, the opposite pattern was observed when the choice-RT task required manual responses. Thus, the response modality for the choice-RT task influenced the maintenance of a concurrent WM task when that task required the same domain-specific WM resources, but did not interfere when they required distinct resources.

Taken together with the findings from the experiments presented here, the results suggest dual-task costs can be avoided when the two tasks consist of exclusively verbal and exclusively spatial components. This allows the tasks to be processed in distinct subsystems of working memory. When any component of one of the two tasks requires use of the other subsystem, it is possible that a domain general processing system, like the central executive, must be recruited to coordinate the two tasks which could significantly slow response times.

In sum, dual-task costs arise when the two tasks do not consist of exclusively verbal and exclusively spatial information. Only in these unique cases is the interference typically caused by binding multiple stimuli to distinct responses at the same time avoided. When one task requires a spatial code and the other a verbal code, in addition to using distinct input and output modalities, two tasks can be performed simultaneously without costs. In this way, the costs depend on the relationship between the tasks. Thus, when driving and talking on a cell phone, even if using your hand to move the steering wheel when changing lanes requires a spatial code, and responding to your friend on the phone requires a verbal code, the collective maintenance of the two tasks likely contain components that require use of the other subsystem. For example, reading road signs clearly contains a verbal component. Even if reading road signs is not required for turning the steering wheel at a given moment in time, the representation of the combination of the two tasks requires use of both the spatial and verbal systems that leads to impairments in driving.

NOTES

1. With these three t-tests, I am doing one more comparison than I have degrees of freedom. However, because each of these comparisons is theoretically motivated and the presence/absence of dual-task costs are equally motivated hypotheses, I did no corrections.

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APPENDIX A

SUM OF DUAL-TASK COSTS BY PARTICIPANT

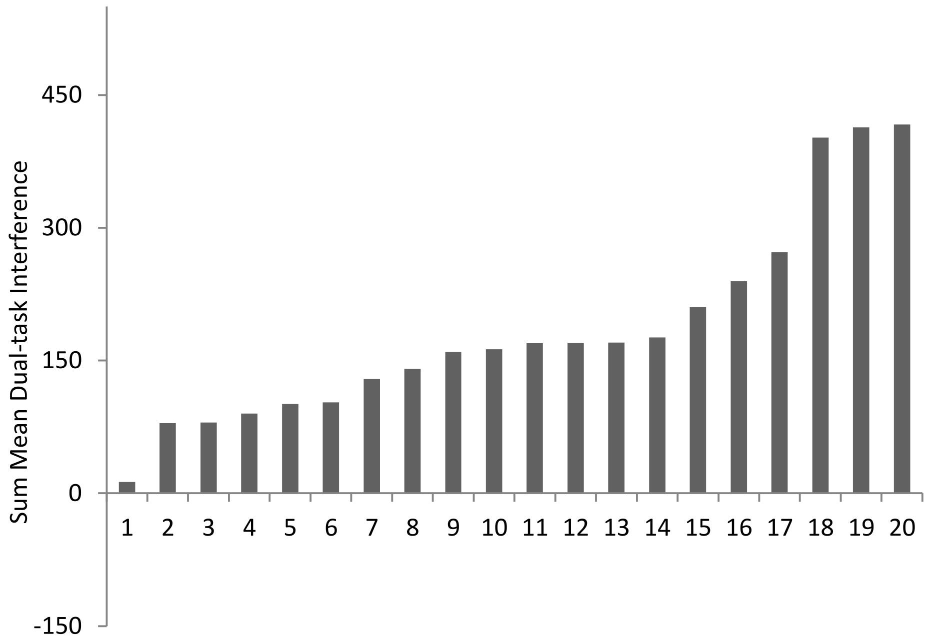

Figure A1. The sum of the mean dual-task costs separated by participant in Experiment 1. The sum of the overall dual-task costs was 185 ms.

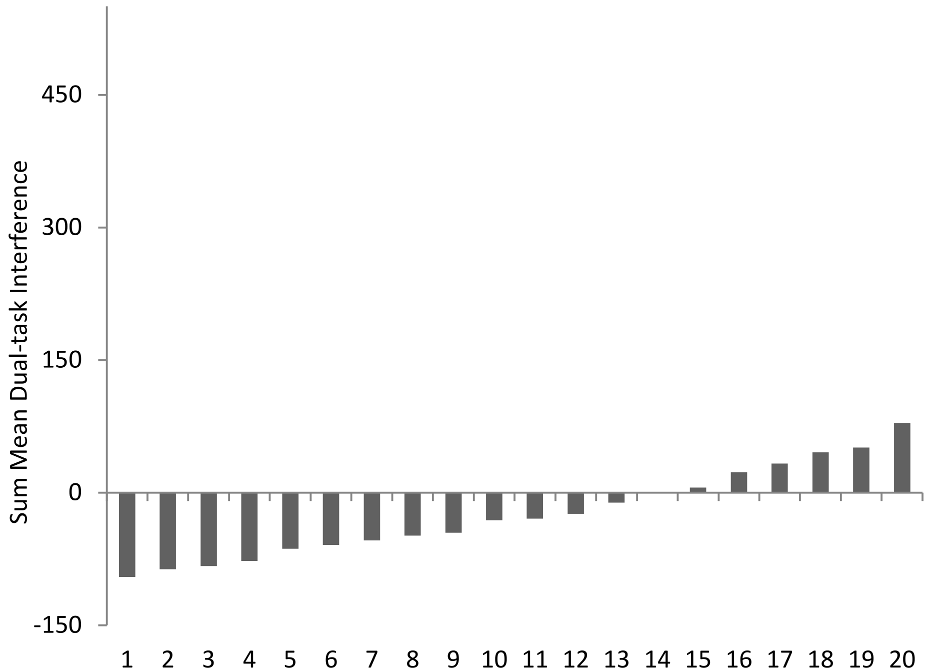

Figure A2. The sum of the mean dual-task costs separated by participant in Experiment 2. The sum of the overall dual-task costs was -24 ms.

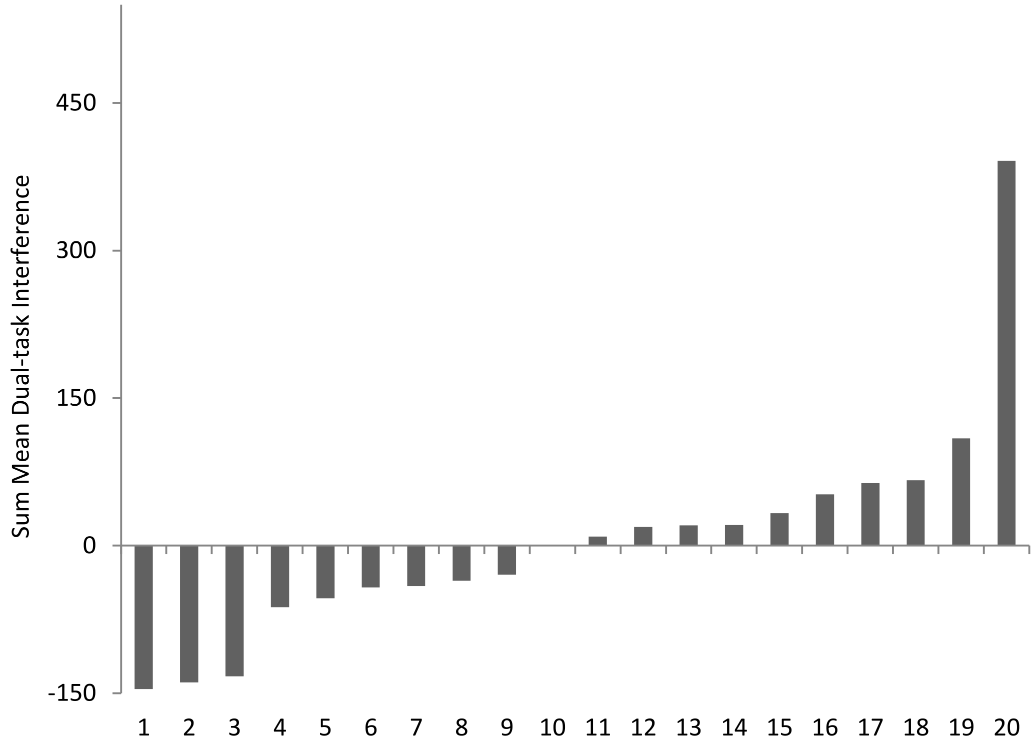

Figure A3. The sum of the mean dual-task costs separated by participant in Experiment 3. The sum of the overall dual-task costs was 5 ms.

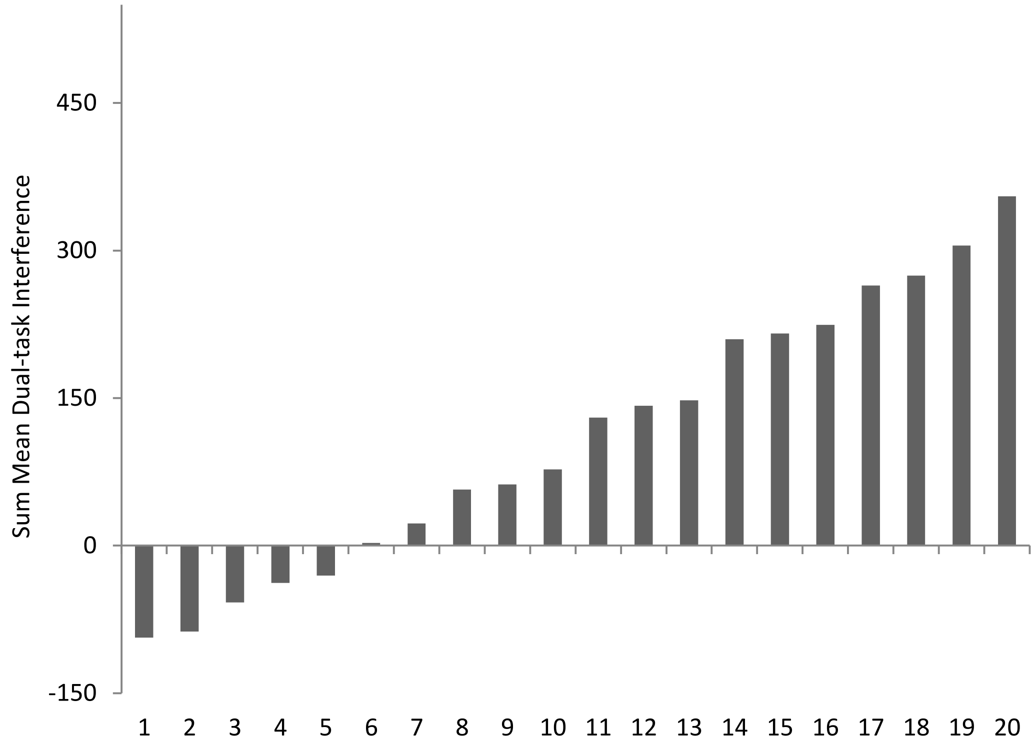

Figure A4. The sum of the mean dual-task costs separated by participant in Experiment 7. The sum of the overall dual-task costs was 109 ms.

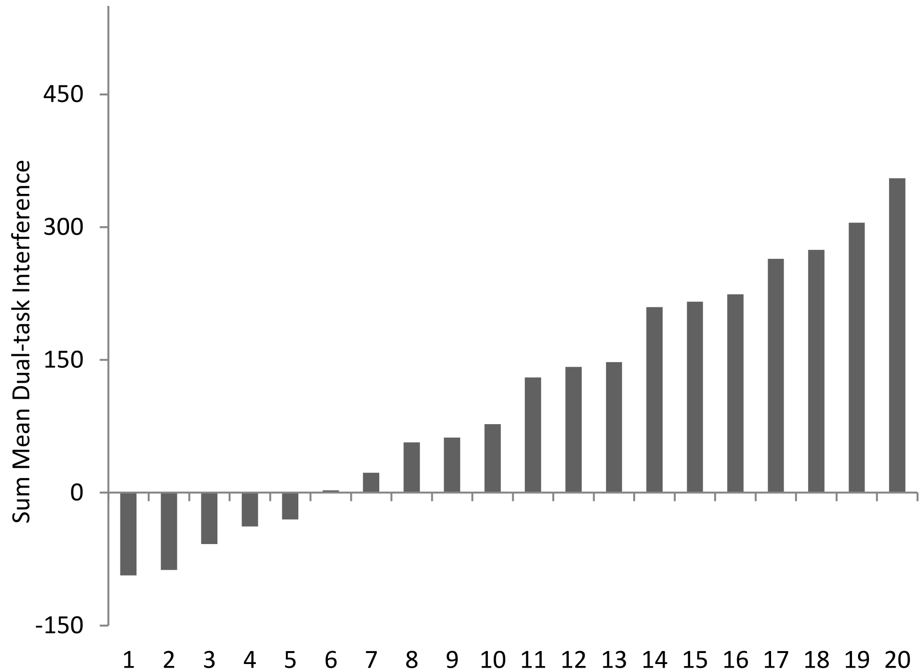

Figure A5. The sum of the mean dual-task costs separated by participant in Experiment 10. The sum of the overall dual-task costs was 106 ms.

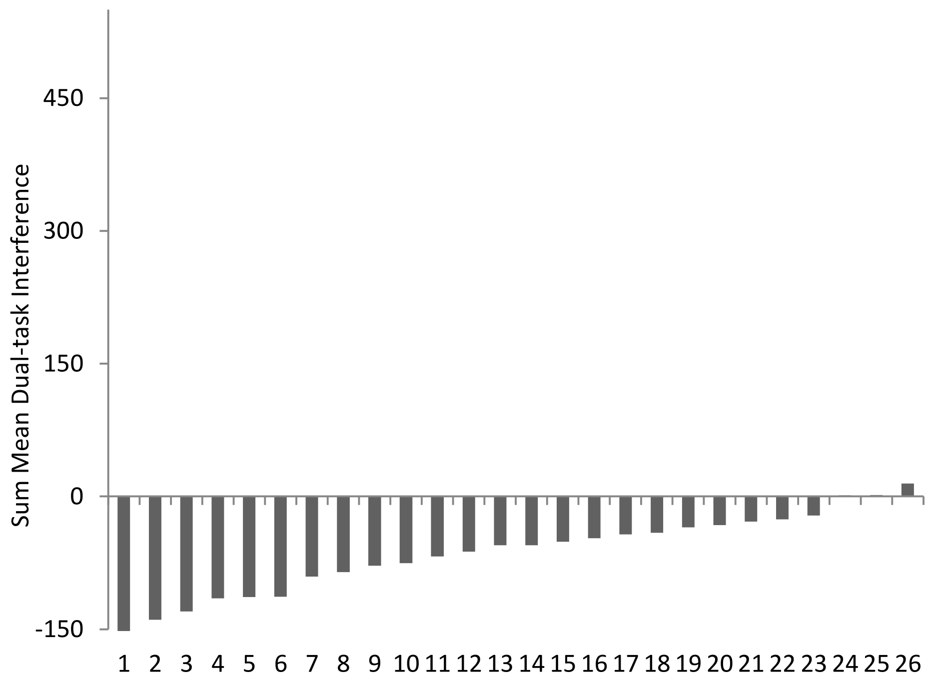

Figure A6. The sum of the mean dual-task costs separated by participant in Experiment 11. The sum of the overall dual-task costs was -66 ms.

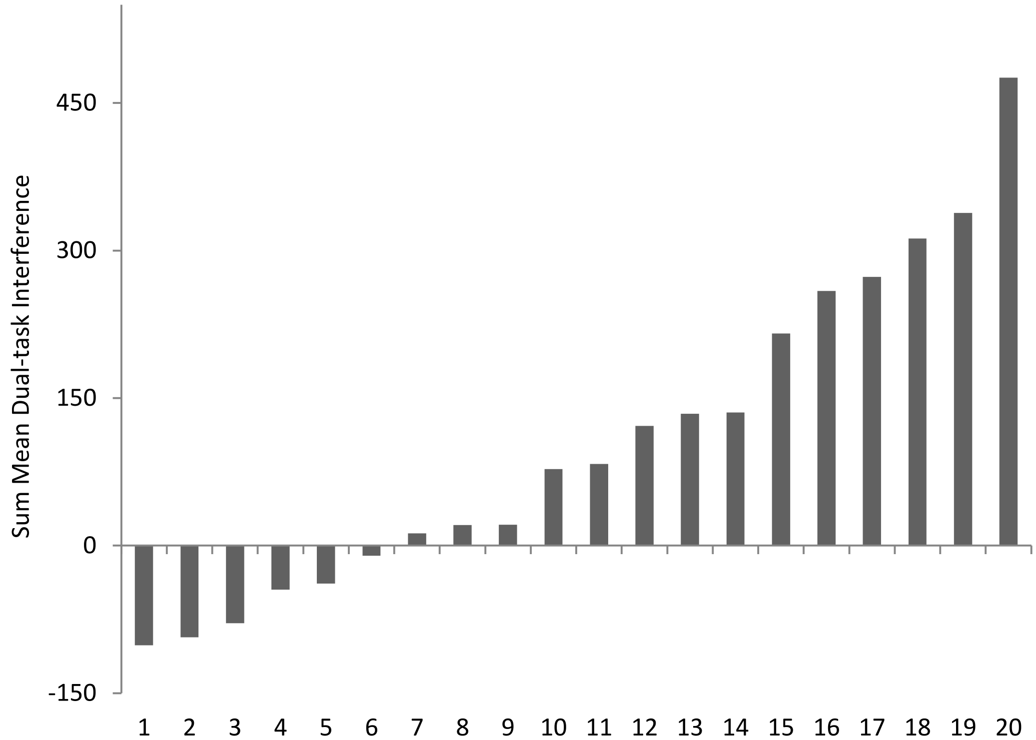

Figure A7. The sum of the mean dual-task costs separated by participant in Experiment 12. The sum of the overall dual-task costs was 106 ms.

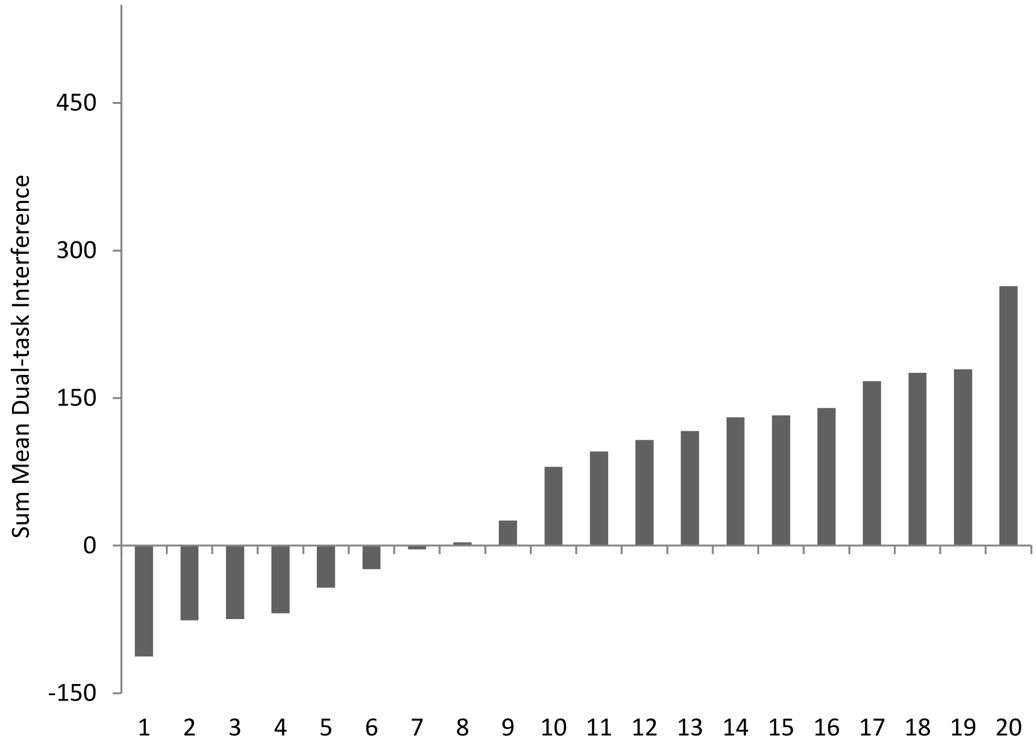

Figure A8. The sum of the mean dual-task costs separated by participant in Experiment 13. The sum of the overall dual-task costs was 61 ms.

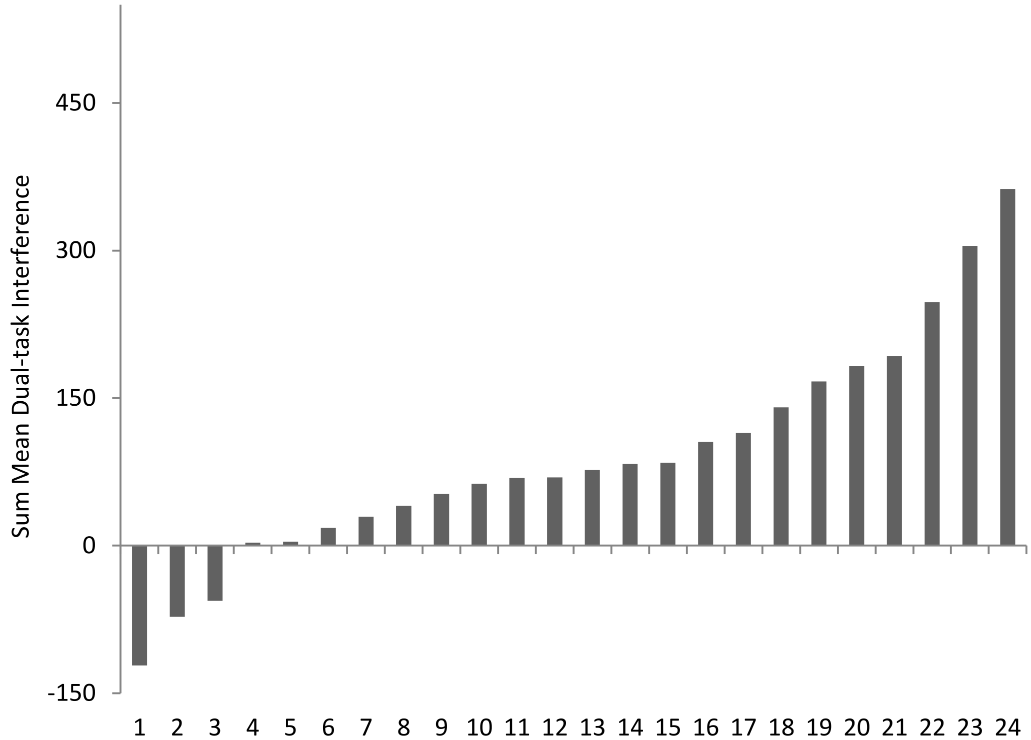

Figure A9. The sum of the mean dual-task costs separated by participant in Experiment 14. The sum of the overall dual-task costs was 90 ms.

APPENDIX B

INSTRUCTIONS FOR EACH EXPERIMENT

Experiment 1 instructions

AV task: “In this block, you will respond to what you hear in your headphones. If you hear the low tone, say “dog.” If you hear the high tone, say “cat.” Be sure to respond as quickly and accurately as possible.”

VM task: “In this block you will see images of letters. If the image is a “V,” press the 1 key on the numeric keypad with your right index finger. If the image is a “W,” press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible.”

Experiment 2 instructions

AV task: “In this block, you will respond to a word that you hear in your headphones. If you hear “dog,” say “dog.” If you hear “cat,” say “cat.” Be sure to respond as quickly and accurately as possible.”

VM task: “In this block you will see pictures of hands making movements. If the hand is depressing the index finger, press the 1 key on the numeric keypad with your right index finger. If the hand is depressing the middle finger, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible.”

Experiment 3 instructions

AV task: “Always do the opposite. In this block, you will respond to a word that you hear in your headphones. If you hear “dog,” say “cat.” If you hear “cat,” say “dog.” Be sure to respond as quickly and accurately as possible.”

VM task: “Always do the opposite. In this block you will see pictures of hands making movements. You should respond by performing the opposite movement with your own right hand. If the hand is depressing the index finger, press the 2 key on the numeric keypad with your right middle finger. If the hand is depressing the middle finger, press the 1 key on the numeric keypad with your right index finger. Please respond as quickly and accurately as possible."

Experiment 4 instructions

AV task: "Always do the opposite. In this block, you will respond to a word that you hear in your headphones. If you hear "dog," say "cat." If you hear "cat," say "dog." Be sure to respond as quickly and accurately as possible."

VM task: "In this block you will see pictures of hands making movements. You should respond by doing what you see. If the hand is depressing the index finger, press the 1 key on the numeric keypad with your right index finger. If the hand is depressing the middle finger, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible."

Experiment 5 instructions

AV task: "In this block, you will respond to a word that you hear in your headphones. If you hear "dog," say "dog." If you hear "cat," say "cat." Be sure to respond as quickly and accurately as possible."

VM task: "In this block you will see pictures of hands making movements. You should respond by doing what you see. If the hand is depressing the index finger, press the 1 key on the numeric keypad with your right index finger. If the hand is depressing the middle finger, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible."

Experiment 6 instructions

AV task: "Always do the opposite. In this block, you will respond to a word that you hear in your headphones. If you hear "dog," say "cat." If you hear "cat," say "dog." Be sure to respond as quickly and accurately as possible."

VM task: "Always do the opposite. In this block you will see pictures of hands making movements. You should respond by performing the opposite movement with your own right hand. If the hand is depressing the index finger, press the 3 key on the numeric keypad with your right middle finger. If the hand is depressing the ring finger, press the 1 key on the numeric keypad with your right index finger. Please respond as quickly and accurately as possible."

Experiment 7 instructions

AV task: "In this block, you will respond to a word that you hear in your headphones. If you hear "red," say "dog." If you hear "green," say "cat." Be sure to respond as quickly and accurately as possible."

VM task: "In this block you will see pictures of hands making movements. If the hand is in the shape of a "V," press the 1 key on the numeric keypad with your right index finger. If the hand is in the shape of a "W," press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible."

Experiment 8 instructions

AV task: "In this block, you will respond to a word that you hear in your headphones. If you hear "red," say "dog." If you hear "green," say "cat." Be sure to respond as quickly and accurately as possible."

VM task: "In this block you will see pictures of hands making movements. If the hand is in the shape of a "V," press the 1 key on the numeric keypad with your right index finger. If the hand is in the shape of a "W," press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible."

Experiment 9 instructions

AV task: "In this block, you will respond to a word that you hear in your headphones. If you hear "dog," say "dog." If you hear "cat," say "cat." Be sure to respond as quickly and accurately as possible."

VM task: "In this block you will see pictures of hands making movements. If the hand is in the shape of a "V," press the 1 key on the numeric keypad with your right index finger. If the hand is in the shape of a "W," press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible."

Experiment 10 instructions

AV task: “In this block, you will respond to a word that you hear in your headphones. If you hear “red,” say “dog.” If you hear “green,” say “cat.” Be sure to respond as quickly and accurately as possible.”

VM task: “In this block you will make button press responses to images that appear on the screen.

If you see this image:

Press the 1 key on the nubmer pad

If you see this image:

Press the 2 key on the number pad

Please make your responses as quickly and accurately as possible.”

Experiment 11 instructions

AV task: “Repeat what you hear. In this block, you will respond to a word that you hear in your headphones. If you hear “dog,” say “dog.” If you hear “cat,” say “cat.” Be sure to respond as quickly and accurately as possible.”

VM task: “In this block you will see two colored circles on each trial. You should respond based on the location of the YELLOW circle. If the yellow circle is on the left, press the 1 key on the numeric keypad with your right index finger. If the yellow circle is on the right, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible.”

Experiment 12 instructions

AV task: “In this block you will respond vocally to sounds. If you hear a whistle, say “dog.” If you hear a bell, say “cat.” Please respond as quickly and accurately as possible.”

VM task: “In this block you will see two colored circles on each trial. You should respond based on the location of the BLUE circle. If the blue circle is on the left, press the 1 key on the numeric keypad with your right index finger. If the blue circle is on the right, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible.”

Experiment 13 instructions

VV task: “Read the word that appears on the screen. In this block you will respond verbally to a word that appears on the screen. If you see “cat,” say “cat.” If you see “dog,” say “dog.” Be sure to respond as quickly and accurately as possible.”

AM task: “In this block you will hear a tone on each trial. You should respond based on the location of the tone. If the tone comes from the left, press the 1 key on the numeric keypad with your right index finger. If the tone comes from the right, press the 2 key on the numeric keypad with your right middle finger. Please respond as quickly and accurately as possible.”

Experiment 14 instructions

AV task: “In this block you will respond vocally to sounds. If you hear the word “cat,” say “cat.” If you hear a tone, say “dog.” Please respond as quickly and accurately as possible.”

VM task: “In this block you will see images in the middle of the screen. If an image of a hand with the index finger depressed appears, please press the 1 key. If a red square appears, press the 2 key. Please respond as quickly and accurately as possible.”