Parallel Response Selection Disrupts Sequence Learning Under Dual-Task Conditions

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Some studies suggest that dual-task processing impairs sequence learning; others suggest it does not. The reason for this discrepancy remains obscure. It may have to do with the dual-task procedure often used. Many dual-task sequence learning studies pair the serial reaction time (SRT) task with a tone-counting secondary task. The tone-counting task, however, is not ideal for studying the cognitive processes involved in sequence learning. The present experiments sought to identify the nature of the interference responsible for disrupting sequence learning in dual-task situations using more tractable dual-task procedures. Experiments 1 and 2 showed that parallel-interfering central processing disrupts sequence learning. Experiment 3 used a novel combination of the SRT task as the secondary task in a psychological refractory period procedure. It showed that SRT task performance can be disrupted without disrupting sequence learning when that disruption involves a response-selection bottleneck rather than parallel response selection. Together, these results suggest that it is the overlap of central processes involved in successfully performing the 2 tasks concurrently that leads to learning deficits in dual-task sequence learning.

Keywords: central capacity sharing, dual-task interference, psychological refractory period (PRP), response-selection bottleneck, serial reaction time (SRT) task

Learning and performing sequences of actions are critical for many tasks people perform every day (e.g., driving, parallel parking, and playing musical instruments). Indeed, Karl Lashley (1951) noted that sequential organization of movements is a central aspect of behavior. In fact, sequence learning is so essential that even infants can extract language-related sequential information from the auditory speech sounds in their environment (Saffran, Aslin, & Newport, 1996). Typically, learning and performing the motor sequences required for many everyday tasks are not done in isolation. People often must perform sequences of behaviors for multiple tasks simultaneously. Furthermore, this multitask learning is often imperfect. In a seminal study of sequence learning, Nissen and Bullemer (1987) reported that participants were unable to learn sequence information under dual-task conditions. They suggested that this dual-task learning impairment results from the lack of available attentional resources sufficient to support sequence learning and dual-task performance concurrently.

Cognitive psychologists have investigated the cognitive and neural mechanisms underlying implicit sequence learning for over two decades. Despite the abundance of research in the area, fundamental questions remain about the nature of the attention, memory, and control systems required to learn and perform organized sequential behaviors in both single- and multiple-task situations. The goal of the present research was to investigate the conditions under which multiple-task processing disrupts sequence learning. This knowledge may lead to a better understanding of the underlying cognitive processes responsible for sequence learning and may lead to important insights into the organization of the human information-processing system. Such insights may point to conditions that will allow researchers to improve the efficiency of sequential learning both in the laboratory and in real-world situations.

Confusion surrounding implicit sequence learning is not surprising considering that even the definition of the term implicit learning is controversial: Some scientists characterize it as unintentional (Frensch, 1998) or unconscious learning (Jiménez & Méndez, 1999), whereas others say it is simply a form of associative learning and not necessarily unintentional or unconscious (Cleermans, Destrébecqz, & Boyer, 1998). Although various researchers define the phenomenon differently, most agree that implicit learning is learning without awareness (e.g., Hazeltine, Grafton, & Ivry, 1997; Schendan, Searl, Melrose, & Stern, 2003). However, like implicit learning, the term awareness is poorly defined, and therefore such a definition does little to clarify the issue.

An operational definition of implicit learning is important to many researchers interested in differentiating between implicit and explicit memory systems (e.g., N. J. Cohen & Eichenbaum, 1993; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Schendan et al., 2003). Although identifying functional dissociations between these memory systems is important, some researchers suggest that identifying a distinct role for either of these systems in sequence learning may be unrealistic. That is, tasks used to study sequence learning may be unrealistic. That is, tasks used to study sequence
learning are not process pure (i.e., they likely involve both implicit and explicit memory processes; Destrebecqz & Cleeremans, 2001; Destrebecqz et al., 2005).

In an attempt to circumvent the problem of distinguishing between the unknown influences of multiple memory systems, other researchers have used a different approach to investigate sequence learning. The cognitive processing approach (e.g. Frensch, Lin, & Buchner, 1998; Heuer & Schmidtke, 1996; Howard, Mutter, & Howard, 1992; Studler, 1995; Willingham, 1999; Willingham, Nissen, & Bullemer, 1989), which is used here, focuses on the influence that specific cognitive processes have on sequence learning and sequential behavior rather than on the influence of entire memory systems. A brief review of the major theories of sequence learning and the effect of multiple-task performance on this learning is included in the rest of this introduction.

We lay out the various theories in the dual-task sequence learning literature that attempt to account for the controversial finding that secondary tasks sometimes impair spatial sequence learning. We review the role of capacity-limited attentional resources, task organization, task integration, multiple processing systems, and the possibility that learning is not impaired but simply cannot be expressed in the presence of a secondary task. Next, we discuss theories for the effect of multiple-task performance on cognitive processing. We also introduce the response-selection bottleneck hypothesis and the psychological refractory period procedure. Reviewing this literature sets the stage for discussing how we can use a cognitive processing approach and knowledge from the human multiple-task performance literature to better understand how and why performing a secondary task interferes with sequence learning.

The Serial Reaction Time (SRT) Task

Multiple-task sequence learning is ubiquitous. It is a fundamental human endeavor that people engage in nearly every day (Clegg, DiGrolamo, & Keele, 1998). For example, multiple-task sequence learning occurs when an office employee types at his or her computer while listening to the radio or to the conversations of his or her coworkers and when a musician plays his or her instrument while listening to and interacting with other musicians in the orchestra. Sequence learning outside the laboratory, however, is extremely complicated. For example, consider a pianist learning a musical score (cf. Landau & D’Esposito, 2006). Learning the proper sequences of behaviors is undeniably important. However, this task involves many intricacies that are difficult, if not impossible, to control in the laboratory. For example, learning a new piece of music is goal directed and explicit; it involves varying amounts of visual preview of the upcoming notes and preparation for the upcoming responses; and the notes may be played with different fingers, different force, and different timing. To control for these and other factors, Nissen and Bullemer (1987) developed the SRT task to investigate in the laboratory the implicit procedural mechanisms involved in sequence learning.

The SRT task is now one of the standard procedures used to study sequence learning. In this task, participants are presented with several (typically 3–6) possible stimulus locations. A target appears in one of these locations on each trial, and participants indicate the location of the target by pressing a button with a predetermined finger. Unknown to participants, the stimuli appear in an ordered sequence. Typical sequences are 6–12 stimulus positions long and repeat continuously over the course of the experiment. With practice, reaction times (RTs) usually decrease more with a sequenced task than with an unsequenced version of the same task;1 this performance improvement likely occurs due to knowledge of the sequence.

It is important to note that results using the SRT task are not unique. Other tasks, such as tracing (Grafton, Salidis, & Willingham, 2001), triplet learning (Howard, Howard, Dennis, & Kelly, 2008), and serial search (Goschke, 1998), have produced similar results. Furthermore, Witt and Willingham (2006) showed that sequence learning occurs with an SRT task using responses more complicated than standard key presses (e.g., push a button, turn a dial, grasp a knob, and flip a switch). Therefore, the standard SRT task, which is used here, likely measures processes involved in more complicated “real world” sequence learning situations.

Nissen and Bullemer (1987) measured sequence learning by comparing mean RTs on sequenced and unsequenced versions of this perceptual motor task. Another measure of sequence learning, first used by Willingham et al. (1989), is the effect on mean RT of switching from a sequenced to an unsequenced task. This transfer effect compares the mean RT from a block of unsequenced trials with the mean RT from surrounding blocks of sequenced trials. RTs are typically faster for sequenced compared with unsequenced blocks of trials, even though participants are rarely aware of the change in the trial structure between one block and the next. Thus, despite this lack of awareness, participants’ behavior indicates that they can learn sequences under this type of single-task SRT procedure. The ability to learn a sequence under dual-task conditions, however, remains an issue of debate in the literature, with some studies reporting intact dual-task sequence learning (e.g., Frensch et al., 1998; Frensch & Miner, 1994; Grafton, Hazeltine, & Ivry, 1995; Jiménez & Vázquez, 2005; Keele, Jennings, Jones, Caulton, & Cohen, 1995; McDowall, Lustig, & Parkin, 1995; Schvaneveldt & Gomez, 1998; Shanks & Channon, 2002; Studler, 1995) and others reporting impaired sequence learning in dual-task situations (e.g., Frensch, Buchner, & Lin, 1994; Frensch, Wenke, & Runger, 1999; Heuer & Schmidtke, 1996; Nissen & Bullemer, 1987). This controversy limits researchers’ fundamental understanding of sequenced behavior. In the present research, we sought to resolve these contradictory findings.

Dual-Task Sequence Learning

The typical dual-task sequence learning procedure pairs the SRT task with a secondary tone-counting task. In this task, participants hear a high- or low-pitch tone on each trial and must keep a running count of the number of times one of the tones is presented. As we have noted, whether or not learning can occur in such a procedure is contentious, and a number of different hypotheses exist to account for why learning is sometimes impaired with the dual-task SRT procedure.

Some researchers suggest that sequence learning requires attentional resources (e.g., Curran & Keele, 1993; Nissen & Bullemer, 1987). According to this attentional resource theory, performing a

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1 In this article we use unsequenced to mean trials in which the sequence presented is either random or not previously presented to participants.
secondary task under dual-task conditions diverts attention, which is a finite and limited resource (cf. Kahneman, 1973), from the SRT task and thus impairs sequence learning.

Like implicit learning and awareness, the idea of attentional resources has been criticized for its lack of specificity and theoretical usefulness (cf. Navon, 1984). Additionally, some researchers suggest that there may be multiple attentional processes whose capacity may be independent of each other (Navon & Gopher, 1979; Wickens, 1984). Thus, impairments in dual-task sequence learning may stem from interference effects in specific processes (A. Cohen, Ivry, & Keele, 1990; Frensch et al., 1998; Heuer & Schmidtke, 1996; Stadler, 1995) rather than from a decrease in a general pool of attention. Furthermore, evidence suggests that under certain circumstances people can divide their attention without cost between two simultaneous tasks (e.g., Allport, Antonis, & Reynolds, 1972; Greenwald & Schulman, 1973; Hazeltine, Teague, & Ivry, 2002; Oberauer & Kliegl, 2004; Ruthruff, Hazeltine, & Remington, 2006; Schumacher et al., 2001; Shaffer, 1975), which calls into question the basic assumption that attentional resources are necessarily capacity limited.

Other researchers propose that sequence learning is an automatic process that does not require attentional resources (Frensch & Miner, 1994). According to this automatic learning hypothesis, sequence learning does not require attention, and therefore adding a secondary task does not affect or minimally affects the acquisition of sequence knowledge; rather, a secondary task affects the expression of that knowledge (later termed the suppression hypothesis; Frensch, 1998; Frensch et al., 1998; Frensch et al., 1999). According to this hypothesis, other processes (viz., task scheduling) affect overall RTs and thus obscure the effect of sequence learning in the dual-task procedure (Frensch et al., 1998, 1999).

Another possible locus of interference of sequence learning under dual-task conditions is proposed in the organizational hypothesis. Stadler (1995) observed that only a subset of secondary task stimuli (e.g., the high tones) require participants to update their count in working memory. Stadler suggested that it is this trial-by-trial variability in secondary task requirements that impairs sequence learning. He provided support for this idea by demonstrating that simply inserting random short and long response–stimulus intervals (RSI) between trials in the SRT task produces a similar disruption of sequence learning.

The task integration hypothesis is yet another proposed theory accounting for the effect of dual-task processing on sequence learning (Schmidtke & Heuer, 1997). This hypothesis states that the stimuli for the two tasks are combined during processing and, therefore, are incorporated into the same sequence. In the standard dual-task SRT procedure, the tone stimuli are unsequenced, and thus the integrated visual-tone sequence is complex and difficult or impossible to learn.

Similarly, Keele and colleagues (2003) proposed a two-system theory of sequence learning in which learning may be supported both by unidimensional learning systems, which integrate inputs within a modality or dimension, and multidimensional learning systems, in which cross-modal input integration is possible. These systems work in parallel to acquire sequence knowledge under single-task conditions. In dual-task situations, however, the multidimensional system attempts to integrate the stimuli for both tasks and thus its affect on sequence learning is impaired, and sequence learning consequently decreases.

To conclude this section, there are a number of hypotheses to explain how and why sequence learning is disrupted under dual-task conditions. Not all of these hypotheses are mutually exclusive; however, the literature has yet to agree on the mechanism or mechanisms for how sequence learning or performance is disrupted by the addition of a secondary task. This lack of consensus limits researchers’ understanding of sequence learning both in the laboratory and in the real world. Further research is necessary to resolve this controversy. We propose that consideration of other lines of closely related research can shed light on this debate. We now introduce several influential theories of multiple-task performance, developed outside the scope of studies of sequence learning, before attempting to integrate these ideas in our experiments.

Cognitive Processing in Dual-Task Performance

Investigating the effects of multiple-task performance on information processing has a long history in cognitive psychology (for a review, see Meyer & Kieras, 1997a; Pashler, 1994a; Pashler & Johnston, 1998). This research often conceptualizes attentional resources as capacity limits within specific cognitive processes. Thus, particular combinations of tasks may occupy the processing capacity of specific cognitive stages (Pashler, 1994b). Applying this logic to sequence learning suggests that learning may be impaired to the extent that a secondary task sufficiently interferes with, delays, or otherwise impedes one or more of the processes required to learn a sequence (cf. Frensch et al., 1994, 1998; Heuer & Schmidtke, 1996; Stadler, 1995).

We can think of the processing required to perform the SRT task as requiring at least three processing stages (Donders, 1969; Meyer & Kieras, 1997a; Pashler, 1994a; Sternberg, 1969). After a stimulus is presented, one must first encode it, and then select the appropriate response to that stimulus among competing alternatives, before finally executing the selected response. Processing in each of these stages may be affected by the addition of a secondary task, and, theoretically, disruption of any one of these stages may affect the efficiency of sequence learning.

One influential procedure used to study dual-task processing is the psychological refractory period (PRP) procedure (for a review, see Meyer & Kieras, 1997a; Pashler, 1994a; Pashler & Johnston, 1998). In the PRP procedure, participants are presented with a series of discrete trials. On a given trial, a stimulus is presented, and participants must respond quickly and accurately to that stimulus (the primary task). After a variable stimulus onset asynchrony (SOA), a second stimulus is presented, and participants must respond quickly and accurately to that stimulus as well (the secondary task). Typically, participants give priority to the primary task. As a result, primary task RTs usually remain relatively constant across SOA, whereas secondary task RTs increase as SOA decreases. This is known as the PRP effect. Under many circumstances, the PRP effect is hypothesized to be due to a central processing bottleneck.

Researchers, however, have been even more specific about the locus of the central processing bottleneck. Through a series of experimental manipulations (e.g., variable stimulus contrasts, display size, and stimulus–response compatibility), researchers have been able to identify response selection as the specific process that is often delayed in the PRP procedure. For example, Pashler
(1984) used a secondary visual search task and demonstrated that manipulations of both display contrast and display size affected visual search RT less under dual- than single-task conditions. This suggests that the processing stages affected by display contrast and set size (viz., stimulus encoding) proceeded in parallel with performance of the primary task. Conversely, McCann and Johnston (1992) demonstrated the effect size of a manipulation of secondary task stimulus–response compatibility (a factor affecting response selection) did not interact with SOA. This suggests that response selection for the secondary task did not begin until after response selection for the primary task was complete (i.e., a response-selection bottleneck; see Figure 2b).

However, the exact locus and nature of the processing bottleneck is controversial. Some contrary research suggests that the processing bottleneck may occur after response selection (Keele, 1973). Still other research suggests that the response-selection bottleneck may be a strategic (e.g., Meyer & Kieras, 1997a, 1997b; Meyer et al., 1995; Schumacher et al., 1999, 2001), rather than a structural (e.g., Byrne & Anderson, 2001; Pashler, 1994a; Ruthruff, Pashler, & Klaassen, 2001), limitation of the human information-processing system. These controversies concerning the exact locus and nature of the bottleneck mechanism may not be relevant to sequence learning because the tasks most often used (and the ones used here) involve separate stimulus (visual and auditory) and response (manual and vocal) modalities; therefore, the interference between the tasks likely occurs during central (e.g., response selection) processing stages. Additionally, both strategic and structural versions of the response-selection bottleneck predict a bottleneck at the levels of practice (viz., one session) used here and in most sequence learning experiments (cf. Schumacher et al., 1999).

This multiple-task literature raises important theoretical questions about sequence learning under dual-task conditions: which processes are critical for sequence learning, and to what extent must the affected processes be occupied by a secondary task before sequence learning will be impaired? Answering these questions will contribute substantially to a fundamental understanding of sequenced behavior. Research exists investigating the influence of the various processing stages (i.e., stimulus encoding, response selection, response execution) on sequence learning under single-task conditions. A number of researchers emphasize the role that stimulus encoding plays in learning a sequence (Clegg, 2005; A. Cohen et al., 1990; Grafton et al., 2001; Howard et al., 1992; Keele et al., 1995; Mayr, 1996; Verwey & Clegg, 2005). Others suggest that response selection is the locus of sequence learning (Bischoff-Grethe, Geordet, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000). Still others propose that sequence learning is based on stimulus–response pairings within the response-selection stage (Deroost & Soetens, 2006; Hazeltine, 2002; Schwab & Schumacher, 2009; Willingham et al., 1989). The experiments presented here investigate this controversy and extend this investigation by integrating sequence learning with knowledge about dual-task processing from the multiple-task performance literature. They show that small adjustments to the standard dual-task SRT procedure as well as combining the SRT task with the PRP procedure have significant effects on both sequence learning and task performance overall. These results have implications for theories of sequence learning and offer insights for theories of multiple-task performance unrelated to sequence learning.

Experiment 1

To address the issue of the locus of interference responsible for the disruption of sequence learning under dual-task conditions, we must use tasks that allow for such an analysis. Unfortunately, there are inherent limitations in the secondary task typically used in dual-task SRT experiments (viz., the tone-counting task) that make this cognitive processing approach difficult. First, the tone-counting task involves many cognitive processes (e.g., stimulus identification, working memory maintenance, and working memory updating) whose effects on dual-task performance are unknown (Stadler, 1995). Second, the tone-counting task is continuous across blocks of trials and only requires a response at the end of each block of trials. Without a response on each trial, it is difficult to determine which process or processes are affected by the simultaneous performance of two tasks (cf. Pashler, 1994a). That is, it is not always possible to know whether participants processed both task stimuli simultaneously or whether they staggered their processing so that each stimulus was processed sequentially.

To address these limitations and investigate process overlap systematically, we implemented a number of changes to the standard dual-task SRT procedure. We used a discrete auditory-vocal tone-identification task in the present study, which required a response on each trial. This task has several advantages over the tone-counting task. First, it is less complex (e.g., it does not require updating and maintaining a count of the number of tones in working memory across a block of trials). Second, because a response is made on every trial, we have a measure of the processing overlap for each task on a trial-by-trial basis. By comparing individual task RTs on a given trial, we can identify not only processing overlap, but we may also be able to infer some aspects of the organization of those processes.

A similar study by Schmidtke and Heuer (1997) used an auditory go/no-go secondary task rather than the typical tone-counting task and reported impaired dual-task sequence learning. This go/no-go task solves many of the problems inherent in using a tone-counting secondary task. However, Schmidtke and Heuer used a short (i.e., 200-ms) RSI between the primary task visual stimuli. The secondary auditory go/no-go stimulus was presented during the RSI. Because of the short RSI, it is quite possible that processing of the secondary auditory go/no-go task was not complete before the visual stimulus for the subsequent trial appeared, and therefore secondary task processing on a given trial may have carried over into the next trial, thus obscuring which task was primary on any particular trial (cf. Keele et al., 2003).

To overcome this limitation, in addition to a discrete tone-identification task, we also used an intertrial interval (ITI) of 2 s to ensure ample time for participants to complete each task prior to the onset of the subsequent trial. This is not a novel modification. Long ITIs have been used previously to investigate sequence learning (i.e., Heuer & Schmidtke, 1996; Shin & Ivry, 2002; Willingham, Greenberg, & Thomas, 1997).

Finally, in Experiment 1 we varied the SOA between the tasks across the three experimental groups. For the single-task groups, only the SRT task was performed. For the dual task: short group,
the visual SRT task stimulus and the auditory tone-identification task stimulus occurred simultaneously (SOA = 0 ms). For the dual task: long group, the auditory stimulus sounded 750 ms after the visual stimulus (SOA = 750 ms). By varying the SOA, we can directly manipulate the overlap in processing between the two tasks across groups.

Method

Participants

Thirty-nine naïve undergraduates (ages 18–22, 12 men and 27 women) from the Georgia Institute of Technology participated in this experiment in partial fulfillment of a course requirement. Participants gave informed consent prior to beginning the experiment, and all participants were treated according to guidelines approved by the American Psychological Association (American Psychological Association, 1992).

Stimuli and Apparatus

Participants sat approximately 60 cm from the computer monitor in a quiet semidark room. Stimulus presentation was controlled with a Dell Dimensions 3000 personal computer. Visual stimuli were presented on a Dell Trinitron 17-in. (43-cm) monitor (1024 × 768, 85 Hz). Auditory stimuli were presented through Philips HN110 noise canceling headphones. The experiment was programmed using Eprime software (Schneider, Eschman, & Zuccolotto, 2002). Responses were made with a specially constructed response keypad with two groups of keys, one group for the index and middle finger of each hand. Vocal responses were made by speaking into an Audio-Technica ATR20 unidirectional microphone connected to a Psychology Software Tools serial response box.

Two spatial sequences of trials were used in the SRT task performed in this experiment. Both have been used previously (Shanks & Channon, 2002; Wilkinson & Shanks, 2004), and both followed the statistical rules outlined by Reed and Johnson (1994); namely, the sequences were identical in terms of position, transition, and reversal frequency, as well as rates of full coverage (i.e., average number of targets presented so that every possible location is used at least once).

Design and Procedure

The SRT task. Four evenly spaced white annuli were presented horizontally in the center of a black display on the computer monitor. The diameter of each annulus subtended 3.34° of visual angle. Two annuli were presented on either side of a white fixation cross; the fixation cross subtended 0.95° × 0.95° of visual angle. The two inner annuli were positioned 2.86° to either side of the fixation cross, and the outer annuli were positioned 3.34° from the outer edge of the inner annuli. The entire horizontal display subtended 26.71° of visual angle horizontally and 3.34° of visual angle vertically. On each trial, one of the annuli was shaded (white). This shaded circle served as the target stimulus for that trial. Participants made a compatible key press to the location of the stimulus. That is, they responded to the leftmost target with their left middle finger, the left inner target with their left index finger, the right inner target with their right index finger and the rightmost target with their right middle finger.

Tone-identification task. Two groups of participants also performed a secondary auditory vocal tone-identification task. On each trial, one of two tones was presented for 40 ms. Participants responded to a 440-Hz tone by saying “low” and to a 1,760-Hz tone by saying “high.”

Groups. Participants were randomly assigned to one of three groups: single task (ST; 14 participants), dual task: long (DT:L; 13 participants), and dual task: short (DT:S; 12 participants). All participants performed 13 blocks of trials. Each block consisted of 96 trials each. The ST group performed the SRT task only. Both dual-task groups performed the SRT and tone-identification task on each trial.

Trials. For all participants, the experiment began when the fixation cross and four annuli appeared on the screen for 1,000 ms. Following that, a visual target (shaded circle) appeared in one of the four locations and remained on screen for 100 ms. After the target disappeared, the four annuli and the fixation cross remained on screen for 1,900 ms before the next target appeared.

The targets followed one of two sequences. For half the participants in each group, one sequence order (S1) was used in Blocks 1–11 and 13, and a different one (S2) was used in Block 12. For the other half of the participants, S2 was used in Blocks 1–11 and 13, and S1 was used in Block 12. To reduce explicit knowledge of the sequence, all blocks, both sequenced and unsequenced, began at a random point in the sequence.

For the ST group, only the SRT task stimuli were presented. For the DT:S group, on each trial the visual and auditory stimuli were presented simultaneously (SOA = 0 ms). For the DT:L group, the auditory stimulus was presented 750 ms after the visual one (SOA = 750 ms).

Instructions and feedback. The participants were not told about the sequence in the SRT task. Participants in the ST group were instructed to respond to the visual task as quickly and accurately as possible. Participants in the DT:S and DT:L groups were instructed to respond to both the visual and auditory stimuli as quickly and accurately as possible. They were free to respond to the task stimuli in either order. At the end of each block of trials, the mean RT and accuracy rates for that block were displayed. At this time, participants were encouraged to respond as quickly and accurately as possible in the upcoming block.

Practice. Before the start of the experiment, the ST group completed three practice blocks of the SRT task. These practice blocks were methodologically identical to the actual experimental blocks except that there was no sequence, the blocks consisted of only 20 trials, and RT and accuracy feedback were given following each trial as well as at the end of each block.

For the DT:S and DT:L groups, participants completed five practice blocks. In the first two blocks, they saw the four annuli and the fixation cross display, but no visual stimulus was presented. On these trials, only the auditory stimulus appeared. The second two practice blocks were identical to the practice blocks for the ST group. The final practice block was methodologically identical to the trials in the respective dual-task experimental blocks except that all stimuli were unsequenced. RT and accuracy feedback followed each trial and at the end of each of these five practice blocks.
Explicit knowledge questionnaires. After the SRT portion of the experiment was finished, all participants were asked to complete two paper questionnaires. The purpose of these questionnaires was to evaluate the participants’ level of awareness for the sequence. Evaluating the level of explicit knowledge is important because explicit and implicit knowledge may be fundamentally different from each other and perhaps even supported by different systems (e.g., Aizenstein et al., 2004; Keele et al., 2003; Schendan et al., 2003). In this study, the explicit knowledge questionnaires were modeled after similar questionnaires used by Frensch et al., (1999). The first asked two questions: What do you believe is the goal of this experiment? Did you notice that the shaded circles were presented in a certain sequence? Participants were then asked to describe what they noticed about the sequence.

Regardless of their answers to the first set of questions, participants were then asked to complete a recognition questionnaire. Twenty-four groups of three trials (triplets) were presented, 12 triplets represented part of the sequence, and 12 did not. If a participant recognized a triplet as part of the sequence, or felt that triplets represented part of the sequence, and 12 did not. If a participant recognized a triplet as part of the sequence, or felt that it was a familiar pattern, then he or she responded by writing “yes” next to that triplet. Otherwise, he or she wrote “no.”

Results

Using the same criterion as Reed and Johnson (1994) and others (Rauch et al., 1997; Shanks & Channon, 2002; Verwey & Clegg, 2005; Wilkinson & Shanks, 2004), we excluded participants with an average accuracy of less than 90% on the secondary task from the analysis. On this basis, we excluded one participant from the DT:L group (85% accuracy). We separately analyzed correct RTs and error rates from the remaining participants for each task. We used a significance level of p < .05 for all inferential statistics. We used the Huynh–Feldt adjustment in every instance in which the assumption of sphericity was violated.

The SRT Task

RTs. We analyzed mean RT data with a two-way analysis of variance (ANOVA), with a between-subjects variable for group (ST, DT:S, DT:L) and a within-subjects variable for block (1–11). These data are plotted in Figure 1a. The assumption of sphericity was violated for this analysis (p < .001), so the degrees of freedom were corrected. The ANOVA revealed significant main effects of both group, F(2, 35) = 11.464, p < .001, and block, F(3, 112, 2) = 16.38, p < .001. The interaction was not significant, F(6, 4, 112, 2) = 0.52, p = .80. These results demonstrate that mean RTs differed between the groups and decreased across blocks.

Post hoc comparisons using Tukey’s honestly significant difference (HSD) test revealed that mean RTs for the ST and DT:L groups were not significantly different from each other (p = .76) but that the mean RT for the DT:S group was significantly longer than both of the other two groups (ST, p < .01; DT:L, p < .001).

The transfer effect (i.e., the increase in mean RT on Block 12 compared with the mean RT from Blocks 11 and 13) was of particular interest in this experiment. If sequence learning occurred, then we would expect the mean RT from the sequenced Block 12 to be slower than the mean RT from the unsequenced Blocks 11 and 13. Because of the specificity of this transfer effect prediction, we used one-tailed comparisons in all tests of the transfer effect. As shown in Figure 1b, mean RTs significantly increased after switching to a new sequence for the ST, t(13) = 5.60, p < .001, and DT:L, t(11) = 3.10, p < .01 groups, but mean RTs for the DT:S group were not different, t(11) = 0.28, p = .39. We conducted a Transfer (Block 12 vs. Blocks 11 and 13) $\times$ Group ANOVA comparing transfer effect size across groups. Both the main effects of group, F(2, 33) = 7.96, p < .01, and transfer, F(1, 33) = 26.3, p < .001, were significant. There was also a significant interaction between these factors, F(2, 33) = 6.57, p < .01. Post hoc comparisons using Tukey’s HSD test indicated that the transfer effects for the ST and DT:L groups were not significantly different from each other (p = .78). The transfer effect for the DT:S group, however, was significantly different from the transfer effect for both the ST and DT:L groups (p < .05, in both cases).

Error rates. Mean error rates for the SRT task were 3.5%, 1.1%, and 2.5% for the three experimental groups, ST, DT:S, and DT:L, respectively. We performed an arcsine transformation (p = arcsin(p; Kleinbaum, Kupper, Muller, & Nizam, 1998) to stabilize the variance of the error rates. We analyzed these data with a
two-way ANOVA with the same variables as the RT data. Neither the main effect of group, \( F(2, 35) = 2.66, p = .08 \), nor of block, \( F(10, 350) = 0.48, p = .90 \), was significant. There was a significant interacting effect of group and block, \( F(20, 350) = 1.76, p < .05 \). Error rates for the DT:S and DT:L groups remained relatively stable throughout the experiment, whereas error rates for the ST group increased steadily across blocks: \( M(\text{Block} 1) = 2.7\% \), \( M(\text{Block} 13) = 5.4\% \). \( T \) tests on the transfer effects for each group showed no significant effects for any group: ST, \( t(13) = 0.36, p = .36; \) DT:L, \( t(11) = 1.42, p = .09; \) and DT:S, \( t(11) = 0.64, p = .27 \).

**Tone-Identification Task**

**RTs.** The mean RTs for correct responses to the tone-identification task are shown in Figure 1a. Mean RTs decreased across blocks for both dual-task groups. We analyzed these data with a two-way ANOVA, with a between-subjects variable for group (DT:L; DT:S) and a within-subjects variable for block (1–11). The test of sphericity was again significant (\( p < .001 \)), and so we adjusted the degrees of freedom. The ANOVA revealed significant main effects of group, \( F(1, 22) = 6.51, p < .05 \), and block, \( F(3, 78.5) = 4.00, p < .01 \). As with the RTs from the SRT task, tone-identification RTs for the DT:S group were significantly slower than RTs for the DT:L group. Again, there was no significant interaction, \( F(3, 78.5) = 1.25, p = .30 \). Additionally, Figure 1a reveals that RTs were unaffected by the change from sequenced to unsequenced visual stimuli on Block 12.

**Error rates.** Mean error rates for the tone-identification task were 2.8\% for the DT:S group and 5.0\% for the DT:L group. We performed the same two-way ANOVA on the arcsine-transformed error data as on the RT data. The assumption of sphericity was again violated (\( p < .05 \)), and degrees of freedom were corrected. The main effect of group approached significance, \( F(1, 22) = 3.79, p = .06 \), indicating that the DT:S group was marginally more accurate on the tone-identification task than the DT:L group and the main effect of block was not significant, \( F(10, 6, 233.2) = 1.04, p = .41 \), indicating that accuracy did not change across blocks. The interaction was not significant, \( F(10, 6, 233.2) = 1.0, p = .45 \).

**Recognition**

When we asked participants what they believed the purpose of the study to be, none mentioned anything similar to sequence or pattern learning. All participants in the DT:S and DT:L groups reported that the study was to test people’s ability to multitask. Most participants in the ST group believed that the study was investigating practice effects.

Mean recognition scores were 57.5\% (SD = 13.6\%), 51.3\% (SD = 10\%) and 51.3\% (SD = 6.2\%) for ST, DT:S, and DT:L groups, respectively (50\% was chance performance). In order to control for the response bias on such recognition questionnaires, we calculated \( d’ \) for each participant (Tunney & Shanks, 2003). We performed \( t \) tests on \( d’ \), and these data revealed that none of the groups’ recognition scores differed significantly from chance: ST, \( t(11) = 1.56, p = .15; DT:L, t(9) = 1.30, p = .23; \) and DT:S, \( t(9) = 1.37, p = .20 \).

**Discussion**

The results from Experiment 1 demonstrate that dual-task processing disrupts sequence learning only when the processing for the two tasks overlap (viz., the DT:S group). When task processing does not overlap (or overlaps minimally), as in the ST and DT:L groups, sequence learning was unimpaired. This suggests that it is simultaneous dual-task processing and not merely switching between two tasks (as in the DT:L group) that disrupts sequence learning.

Although the general trends in the data of impaired learning in the DT:S group suggest that parallel processing in this dual-task condition impairs spatial sequence learning, there is another feature of the Experiment 1 data that must be considered. In Experiment 1, participants were significantly slower in the DT:S group than participants in the other two groups (see Figure 1a). Some of this slowing is likely because they did not benefit from knowledge of the sequence. However, even on the first block, the mean RTs in this group were slower than in the other two groups: DT:S and ST, \( t(24) = 2.30, p < .05 \); and DT:S and DT:L, \( t(22) = 3.45, p < .01 \). Mean RTs for the DT:S group were also slower on the unsequenced Block 12: DT:S and ST, \( t(24) = 2.56, p < .05 \); and DT:S and DT:L, \( t(22) = 3.00, p < .01 \). Thus, participants in the DT:S group were slower even before participants in the other groups were likely to have learned much, if anything, about the underlying sequence, and on blocks where sequence knowledge was not beneficial. This suggests that much of this performance decrement on the SRT task was due to interference from the tone-identification task.

Dual-task interference on the SRT task is, in fact, common in many sequence-learning studies that report a lack of dual-task sequence learning. As previously noted, one popular explanation for the lack of learning under dual-task conditions is that attentional resources are diverted from the primary SRT task to the secondary task (e.g., A. Cohen et al., 1990; Curran & Keele, 1993; Jiménez & Méndez, 1999; Nissen & Bullemer, 1987). This theory predicts the pattern of results found in Experiment 1. That is attention was shared between the two tasks on DT:S trials, slowing both of them.

However, the lack of specificity of what is meant by attention may limit the theoretical usefulness of this theory (cf. Navon, 1984). Additionally, data exist that are difficult for unitary attentional resource theory to explain (for a review, see Meyer & Kieras, 1997a; Wickens, 1980, 1984). Attentional resource theory has been modified to include multiple pools of attention (e.g., spatial and verbal; auditory and visual; Navon & Gopher, 1979; Wickens, 1984). Given that the SRT task involves visual-manual and the tone-counting task involves auditory-vocal modalities, separate resources for spatial and verbal representations and for auditory and visual modalities would seem to undermine the relevance of attentional resource theory for dual-task sequence-learning experiments. Nevertheless, one modification of the attentional resource model that may apply to sequence learning research is the central capacity sharing model, in which the limited resource is specific to central processing; other stages may proceed without capacity limits (McLeod, 1977; Navon & Miller, 2002; Tombu & Jolicœur, 2003, 2005). When two stimuli are presented simultaneously, processing for both can proceed in parallel; however, central processing capacity is shared between them, thus increasing mean RTs (see Figure 2a).

This version of a capacity-limited resource model may be particularly relevant to the present situation given that the distinct perceptual motor modalities of the tasks used here (viz., visual and auditory stimuli and manual and vocal responses) leave central
processes as the likely locus of the dual-task interference (Ruthruff, Pashler, & Hazeltine, 2003). Furthermore, the central processing bottleneck with trial-by-trial variability for which task is primary response selection are also affected by sequence learning (Schwarz & Schumacher, 2009). The 0-SOA procedure used for the DT:S group is similar to the PRP procedure, and, although primary task slowing can occur in the PRP procedure (e.g., Gottsdanker, Broadbent, & Van Sant, 1963; Herman & Kantowitz, 1970; Pashler, 1994b), mean RTs for a primary task are often relatively unaffected by dual-task overlap (e.g., Meyer & Kieras, 1997a, 1997b; Pashler, 1994a). As discussed previously, this is consistent with the central response-selection bottleneck hypothesis that predicts that most, if not all, dual-task interference should occur on the secondary task because response selection for the secondary task must wait until primary task-response selection is complete (Pashler, 1984, 1994a; Welford, 1959).

Despite the seeming inconsistencies between the central bottleneck model’s characteristic primary task RT pattern and the DT:S pattern of results, the central bottleneck model should still be carefully considered because, under certain dual-task circumstances, it does predict primary task slowing in dual-task situations (e.g., Gottsdanker et al., 1963; Herman & Kantowitz, 1970; Pashler, 1994b). The central bottleneck model posits two types of response patterns, particularly with a 0-SOA, as in the DT:S group, that can account for dual-task interference on the SRT task. One pattern involves variability across trials for which task begins central processing first. Because stimuli for both tasks appear simultaneously, on some trials, central processing for the SRT task may begin first, and, as a result, processing for the tone-identification task will be delayed by the central bottleneck (see Figure 2b). On these trials, RTs for the SRT task will be relatively fast, and RTs for the tone-identification task will be relatively slow. Conversely, on some trials, central processes for the tone-identification task may begin first, and the central bottleneck will delay RTs for the SRT task. These trials in which the SRT task is delayed by the bottleneck may account for the dual-task interference on the SRT task.

A second response pattern consistent with the central bottleneck model and dual-task interference on the SRT task involves participants’ use of a response-grouping strategy (cf. Pashler, 1994b; Ruthruff et al., 2006, 2001; Ulrich & Miller, 2008). If responses for both tasks are executed simultaneously after central processing has been completed for both tasks (see Figure 2c), then dual-task interference may occur on both tasks in the presence of a central bottleneck.

We can evaluate whether DT:S participants were using any of these processing strategies (central capacity sharing, a central processing bottleneck with primary task variability, or response grouping) by examining the relationship between correct RTs for the SRT and tone-identification tasks for each trial for each participant. We calculated interresponse intervals (IRIs) on a trial-by-trial basis for each participant. Figure 3 shows the distribution of IRIs for all DT:S participants. The response patterns discussed above predict different distributions of IRIs. When grouping occurs, RTs for the two tasks will be very similar, resulting in very short IRIs producing a “spike” around 0 ms (Pashler, 1994b; Ruthruff, Pashler, & Hazeltine, 2003). A central processing bottleneck with trial-by-trial variability for which task is primary is consistent with the hypothesis that response selection is important for sequence learning.

As discussed previously, dual-task slowing is a common feature in many sequence-learning studies; however, this feature is somewhat surprising in light of the multiple-task performance literature.
predicts a bimodal RT distribution reflecting a combination of SRT-task-response-first trials and tone-identification-task-response-first trials (Pashler, 1994b; Ruthruff, Pashler, & Hazeltine, 2003). Finally, a central capacity model predicts a wide unimodal distribution of positive IRIs because as central processes finish for one task, central resources become available for the other task (Pashler, 1994b; Ruthruff, Pashler, & Hazeltine, 2003; Tombu & Jolicœur, 2003).

As shown in Figure 3, the analysis of the IRIs conducted here revealed that no participant showed evidence of a bimodal RT distribution predicted by a central bottleneck with trial-by-trial primary task variability. The IRIs from 10 participants demonstrate a wide unimodal distribution of positive IRIs, consistent with capacity sharing, whereas the other 2 participants show an IRI spike 0 ms—evidence for response grouping (see Figure 3). Therefore, these data suggest that the dual-task cost on the SRT task was not caused by the use of a response-grouping strategy for most of the participants. However, considering the inherent difference in time required to make a verbal versus a manual response, it may be appropriate to loosen the criterion for identifying participants who grouped their responses from a concentration of IRIs around 0 ms to a concentration of IRIs below 150 ms (although these tasks are similar to ones used by Ruthruff, Pashler, & Hazeltine, 2003, in which response grouping was restricted to IRIs centered around 0 ms). Nevertheless, 2 additional participants are identified as possible groupers when a looser criterion is adopted. By adopting this loose criterion, we identify not only participants who certainly grouped their responses but also those who possibly grouped. With this division, we can be more confident that the overall pattern of data is not influenced by any participants who may have adopted a response-grouping strategy.

The use of a grouping strategy may obscure evidence for sequence knowledge because differences in the duration of the task processing may be absorbed in the cognitive slack (cf. Schweickert, 1978) while the SRT task waits for the tone-identification task (cf. Frensch et al., 1994). Cognitive slack is the period between stages of secondary task processing, in which a secondary task stage must wait until primary task processing completes. In Figure 3, distribution of interresponse intervals for all dual-task: short participants in Experiment 1 (Bin = 50 ms). Each line represents a different participant. Dashed lines represent participants who potentially grouped their responses.

Figure 3. Distribution of interresponse intervals for all dual-task: short participants in Experiment 1 (Bin = 50 ms). Each line represents a different participant. Dashed lines represent participants who potentially grouped their responses.

However, it is not the case that sequence-learning differences between the groups (as shown in Figure 1) was driven by the subset of response groupers in the DT:S group. In fact, the effect sizes for the certain and potential groupers and the other participants were nearly identical. The 4 participants who did or may have grouped their responses had a mean RT of 401 ms for the SRT task and a mean transfer effect of 4 ms. The other 8 participants had a mean RT of 378 ms and a mean transfer effect of 0 ms.2 Significance tests between groups of 4 and 8 participants necessarily have low power; nevertheless, such tests reveal a lack of significant differences between participants who did or may have grouped and those who did not both in overall mean RTs, t(10) = 1.0, p = .34, and sequence learning, t(10) = 0.34, p = .74. Therefore, it is clear that response grouping is not solely responsible for the resulting dual-task interference or for the lack of sequence learning in the DT:S group.

At this point, we have demonstrated that the dual-task interference and the lack of sequence learning in the DT:S group was not simply the product of those participants who engaged in response grouping. Additionally, we have demonstrated that none of our participants engaged in frequent reversals in the task order of central processing. It is possible, however, that bimodality was obscured by very short response-selection stages or noise in the underlying distributions. However, this type of IRI analysis has been used in the literature, and bimodality has been shown with similar tasks (e.g., Pashler, 1994b). Therefore, we believe that the IRI analysis performed here demonstrates that the majority of the participants in the DT:S group displayed a wide range of positive IRIs characteristic of central capacity sharing.

Although the IRI analysis is consistent with the capacity-sharing account of dual-task performance, we need to consider another possibility. A wide unimodal distribution of positive (or negative) IRIs is also expected if participants perform under a central bottleneck with a consistent primary task (Ruthruff, Pashler, & Hazeltine, 2003). However, under this strategy, there should be no delay in processing for the primary task, and therefore no dual-task interference.

There is a way to explain dual-task costs on the primary task under a consistent central bottleneck model, however. Performance may decrease due to changes in how prepared participants are for both tasks when performing in a dual-task situation (e.g., De Jong, 1995; Gottsdanker, 1979, 1980). When stimuli are presented simultaneously and participants do not know which order to process the tasks, they may fail to prepare adequately for the tasks before processing begins. Although we cannot completely rule out this possibility, we do not think such uncertainty plays much of a role.

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2 One might expect that participants using a response-grouping strategy would show sequence learning. However, this would only be predicted if these participants performed under a central bottleneck with SRT task priority. If participants performed under a central bottleneck with tone-identification priority, then the effect of sequence knowledge may be absorbed into the postselection cognitive slack. Unfortunately, when participants group their responses, it is impossible to tell whether their central processes overlapped or not (Pashler, 1994b).
role in the DT:S group in Experiment 1. One feature of the data, which is not conclusive, but should be noted, is that although participants were free to respond in any order, they nearly always (99.6%) responded to the SRT task first just like in the DT:L group, which showed significant sequence learning. Thus, it seems that even in the DT:S group, there was very little ambivalence concerning the order with which participants processed the task stimuli. Additionally, the use of separate stimulus and response modalities is believed to encourage preparation for both tasks (Pashler, 1994b). Therefore, it seems unlikely that differences in levels of task preparation between the dual-task conditions play a major role in the sequence-learning differences reported in Experiment 1. Yet, it remains possible that the between-subjects design used here produced group-level differences in task preparation. The present data are not able to address this issue. We return to this issue in Experiment 3 and the General Discussion section.

Experiment 2

The results from Experiment 1 suggest that parallel central processing may cause the disruption in sequence learning in the dual-task SRT procedure. These results, particularly the lack of sequence learning and the dual-task interference on both tasks in the DT:S group, are somewhat surprising and warrant replication. The dual-task interference on the SRT task and the apparent central capacity sharing are not typical results for dual-task experiments. It is possible that participants may have shared central capacity between the two tasks in Experiment 1 because the procedure emphasized each task equally (e.g., 0-SOA and instructions to respond quickly and accurately to both tasks). This emphasis may have lead to parallel response-selection processing, which consequently disrupted sequence learning.

We tested this hypothesis in Experiment 2 by replicating the DT:S group from Experiment 1 and comparing those results with a new condition in which participants were instructed to emphasize the SRT task. Emphasizing the SRT task should encourage participants to allocate all of their central capacity to that task until it is complete (i.e., perform with a central bottleneck). If it is the sharing of central capacity that disrupts sequence learning, then sequence learning should emerge in this SRT priority group.

Experiment 2 also includes a single-task performance condition after the dual-task replication. With this condition, we can more clearly examine some of the limitations in the IRI analysis from Experiment 1 as well as more completely consider the automatic learning hypothesis—that is, whether dual-task performance disrupts the learning of a sequence or just the expression of that knowledge (e.g., Frensch et al., 1998, 1999).

Method

Participants

Twenty-eight naïve undergraduates (ages 18–26, 18 men and 10 women) from the Georgia Institute of Technology participated in this experiment in partial fulfillment of a course requirement.

Stimuli and Apparatus

All stimuli and apparatus were identical to Experiment 1.

Five second-order conditional sequences that followed the statistical rules defined by Reed and Johnson (1994) were used in this experiment. One sequence was used in the sequenced blocks (Blocks 1–11 and Block 15), and different sequences were used in each of the unsequenced blocks (Blocks 12, 13, 14, and 16; see Table 1). Sequences were counterbalanced across participants.

Design and Procedure

Tasks. Both the SRT task and the tone-identification task were the same as in Experiment 1.

Groups and instructions. Participants were randomly assigned to one of two groups: equal priority instructions (equal priority; 15 participants) and SRT priority instructions (SRT priority; 13 participants). These groups differed only in the instructions given: the equal priority group was told that both tasks were equally important (replication of DT:S group from Experiment 1), and the SRT priority group was told that the visual-manual SRT task was most important and that they must respond to it first.

Trials. All participants completed 12 blocks of 96 dual-task trials with a 0-SOA. After the 12th dual-task block, all participants switched to a single-task condition for four blocks of 96 trials in which only the SRT task was performed (see Table 1).

Practice and feedback. Both practice and feedback were identical to Experiment 1.

Explicit knowledge questionnaires. The follow-up questionnaires were administered at the end of the experiment and were identical to those used in Experiment 1.

Results

As in Experiment 1, we removed participants who performed with less than 90% accuracy on the tone-identification task from the analysis. By this criterion, 3 participants (82%, 84%, and 89% accuracy) were removed from the equal priority group, and 1 participant (89% accuracy) was removed from the SRT priority group. We analyzed correct RTs and error rates from the remaining participants separately for each task. We used a significance level of $p < .05$ for all inferential statistics. We used the Huynh–Feldt

Table 1

Sequence and Task Type for Each Block in Experiment 2

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<th>Block</th>
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<td>16</td>
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D = dual task; S = single task; S1–S5 indicate versions of the sequences used.
adjustment in every instance in which the assumption of sphericity was violated.

The SRT Task

**RTs.** We analyzed dual-task mean RTs as in Experiment 1 with a two-way ANOVA, with a between-subjects variable for group (equal priority and SRT priority) and a within-subjects variable for block (1–11). These data are plotted in Figure 4a. The assumption of sphericity was violated for this analysis (p < .001), so we corrected the degrees of freedom. The ANOVA revealed that mean RTs decreased similarly for both groups across Blocks 1–11. There was a significant main effect of block, F(3.9, 82.3) = 3.67, p < .01, but no significant main effect of group, F(2, 21) = 0.68, p = .52, and no interaction between group and block, F(7.8, 82.3) = 0.65, p = .73.

As in Experiment 1, we used one-tailed t tests to compare the transfer effects for each group. As shown in Figure 4b, mean RTs significantly increased after switching to the new sequence for the SRT priority group both under dual-task, t(11) = 4.16, p < .01, and single-task, t(11) = 2.05, p < .05, conditions. Transfer effects, however, were not significant for the equal priority group under either dual-task, t(11) = 0.81, p = .22, or single-task, t(11) = 0.05, p = .48, conditions.

We conducted a Transfer (Block 11 vs. Block 12 or Block 15 vs. Blocks 14 and 16) × Task (single-task vs. dual-task) × Group ANOVA, comparing transfer effect size across groups. The main effects of task, F(1, 22) = 45.43, p < .01, and transfer, F(1, 22) = 8.66, p < .01, were both significant. The Transfer × Group interaction, F(1, 22) = 5.07, p < .05, was significant, and the Task × Transfer interaction approached significance, F(1, 22) = 3.98, p = .06. Neither the main effect of group, F(1, 22) = 1.96, p = .18, the Task × Group interaction, F(1, 22) = 0.19, p = .67, nor the three-way interaction, F(1, 22) = 0.55, p = .47, were significant. These analyses reveal that dual-task trials were slower than single-task trials and that the difference between RTs for sequenced and unsequenced blocks was significantly greater for the SRT priority group than for the equal priority group. Additionally, the transfer effect was larger for dual-task compared with single-task trials. Finally, equal priority group mean RTs were not significantly different from SRT priority group mean RTs for either the single-task or dual-task blocks.

**Error rates.** Mean error rates for the SRT task were 1.7% for the equal priority group and 1.8% for the SRT priority group. We performed an arcsine transformation to stabilize the variance of the error rates. We analyzed the arcsine-transformed data with a two-way ANOVA, with the same variables as the RT data. The test for sphericity was not significant (p = .46). There was a significant main effect of block, F(10, 220) = 2.31, p < .05, showing that accuracy increased with practice. There was no significant main effect of group, F(1, 22) = 0.01, p = .99, nor was there a significant interacting effect, F(10, 220) = 0.96, p = .48.

Tone-Identification Task

**RTs.** Figure 4a plots the mean RTs for correct responses to the tone-identification task. Mean RTs decreased across blocks for both groups. We analyzed these data with a two-way ANOVA, with a between-subjects variable for group (equal priority and SRT priority) and a within-subjects variable for block (1–11). The test for sphericity was significant (p < .001), so we adjusted the degrees of freedom. The ANOVA revealed a significant main effect of block, F(4.8, 105.6) = 8.08, p < .001. Neither the main effect of group, F(1, 22) = 0.30, p = .59, nor the interaction, F(4.8, 105.6) = 0.73, p = .60, was significant.

**Error rates.** Mean error rates for the tone-identification task were 6.7% for the equal priority group and 6.9% for the SRT priority group. We performed the same two-way ANOVA on the arcsine-transformed error data as on the RT data. The assumption of sphericity was not violated (p = .24). The main effect of block was significant, F(11, 242) = 4.92, p < .001, with accuracy improving across blocks. Neither the main effect of group, F(1, 22) = 0.01, p = .97, nor the interaction, F(11, 242) = 1.33, p = .21, were significant.

Recognition

As in Experiment 1, when we asked participants what they believed the purpose of the study to be, most said the purpose of the study was to evaluate one’s ability to multitask effectively. Mean recognition scores for the included participants were 51.4% (SD = 8.6%) for the equal priority group and 51.4% (SD = 9.1%) for the SRT priority group.

![Figure 4a](image-url)  
**Figure 4.** a: Mean serial reaction time (SRT) and tone-identification (T-I) task reaction times and standard errors across blocks of trials in Experiment 2 for both the equal priority and SRT priority groups. S = sequenced blocks; U = unsequenced blocks. b: SRT task transfer effects for each of the two groups. Asterisks indicate significant transfer effects (p < .05, one-tailed).
From the recognition questionnaires, we calculated $d'$ to control for the response bias as in Experiment 1. A $t$ test revealed that $d'$ was not significantly different from chance for either the equal priority group, $t(11) = 0.56, p = .59$, or the SRT priority group, $t(11) = 0.53, p = .61$.

**Discussion**

In Experiment 2, in both dual- and single-task test conditions, the equal priority group produced no evidence for sequence learning; whereas the SRT priority group showed substantial sequence learning. These data demonstrate that the same tasks and experimental procedure can either produce sequence learning or not, depending on whether dual-task interference affects SRT task performance. These data also replicate and extend the results from Experiment 1 and provide additional information for the mechanisms underlying when and why dual-task processing disrupts sequence learning.

Before considering the implications of these results, we must examine them in detail. First, an analysis of the IRIIs showed that, as in Experiment 1, the lack of evidence for sequence learning was not caused by participants’ use of a response-grouping strategy. No participant in either group showed an IRI spike at 0 ms. Under the loose grouping criterion used in Experiment 1 (spike in IRI < 150 ms), 4 and 5 possible groupers were identified in the equal priority and SRT priority groups, respectively (see Figure 5). All other participants showed the broad distribution of positive IRIIs characteristic of either central capacity sharing or a central bottleneck with consistent primary task. There were no significant differences between the mean RTs or the transfer effects between potential groupers and nongroupers for either group (equal priority: groupers [mean RT = 375 ms; dual-task transfer effect = −8 ms; single-task transfer effect = 5 ms]; nongroupers [mean RT = 388 ms; dual-task transfer effect = 14 ms; single-task transfer effect = −3 ms]; SRT priority: groupers [mean RT = 359 ms; dual-task transfer effect = 30 ms; single-task transfer effect = 19 ms]; nongroupers [mean RT = 349 ms; dual-task transfer effect = 30 ms; single-task transfer effect = 12 ms]).

The second issue to be considered is whether the SRT task experienced dual-task interference in the equal priority group. Here, the results are more equivocal. Visual inspection of the mean RTs in Figure 4 show that the SRT task was slower in the equal priority than in the SRT priority group across nearly all blocks. This is consistent with central capacity sharing; however, this effect was not significant. It may be that capacity was shared between the tasks in the equal priority group, but our study lacked the sensitivity necessary to identify this sharing.

Taken together, the results from Experiment 2 strengthen our hypothesis that interference from parallel central processing disrupts sequence learning. The equal priority group, which likely divided central capacity between the SRT and tone-identification tasks, showed little or no sequence learning (like the DT:S group from Experiment 1). The SRT priority group, however, likely performed under a central bottleneck with SRT task priority and produced substantial sequence learning (like the DT:L group from Experiment 1). Thus, with the exact same tasks and procedure, we were able to induce sequence learning just by manipulating instructions from those that encourage parallel central processing to those that encourage a central bottleneck. Furthermore, there was no change in the pattern of sequence learning when it was tested under single-task conditions. Therefore, contrary to the automatic learning hypothesis (Frensch et al., 1998, 1999), parallel central processing disrupts sequence learning and not just the expression of that knowledge.

The results from Experiments 1 and 2 suggest that SRT learning may be disrupted to the extent that interfering parallel central processing occurs between the SRT and tone-identification tasks. Variability in the amount of central interference across experiments may explain the inconsistent reports in the literature of impaired sequence learning in dual-task situations. To investigate this, we identified the mean RTs for SRT tasks in single- and dual-task conditions from every published study in which a dual-task SRT procedure with three to four possible locations, a tone-counting secondary task, and a higher order deterministic sequence was used. Figure 6 plots the approximate mean SRT task RTs for both single- and dual-task conditions from these experiments. RT is indicated along the top of the figure in 20-ms intervals. Each row represents one experiment from the literature. Each bar represents the difference between the mean RTs for the single-task (left edge) and dual-task (right edge) conditions. That is, the length of each bar represents the amount of dual-task interference on the SRT task.
task in each experiment. Experiments are listed top to bottom from those reporting the least dual-task interference to those reporting the most. The white bars indicate experiments for which significant sequence learning under dual-task conditions was reported. The black bars represent experiments for which disrupted dual-task sequence learning was reported. Notice that most of the studies in which dual-task sequence learning was reported revealed relatively small amounts of dual-task interference on the SRT task (i.e., are toward the top of the figure).

We calculated the correlation between dual-task interference (mean dual-task RT – mean single-task RT) and dual-task sequence learning (dual-task transfer effect; shown in the second column of Figure 6) for each experiment. The correlation was −.18 and not significant (p = .44). Initially, this lack of a significant negative relationship between dual-task interference and amount of sequence learning may suggest a lack of a cognitive relationship between these effects as well. However, although these experiments are similar, the magnitudes of the significant transfer effects (13–95 ms) are quite different—perhaps due to the different participants or differences in the procedures (e.g., the number of stimulus–response pairs, the structure of the sequences).

To overcome these differences, we took advantage of the fact that significant dual-task sequence learning was reported in some of the studies but not in others (white and black bars in Figure 6, respectively). We then compared the amount of dual-task interference between these groups of studies. The results showed that mean dual-task interference was greater for studies in which dual-task sequence learning was not found compared with those studies in which significant dual-task sequence learning was reported, t(19) = 2.18, p < .05.

Taken together, this analysis of the literature and the results from Experiments 1 and 2 offer a possible explanation for the discrepant results frequently reported in the dual-task SRT literature: Higher dual-task costs on SRT task performance are associated with lower levels of sequence learning. The typical dual-task SRT procedure does not attempt to minimize dual-task interference on the SRT task. When not given explicit instructions, different participants in different experiments adopt different performance strategies. Some adopt a strategy emphasizing the SRT task (like our SRT priority group in Experiment 2)—and produce evidence for sequence learning. Others adopt a parallel interfering central processing strategy (like the DT:S group from Experiment...
Experiment 3

The results thus far suggest that in dual-task sequence-learning situations, it is the interference on the SRT task caused by simultaneously active central processes that disrupts sequence learning. If this is true, then sequence learning should be unimpaired in a dual-task situation that does not involve parallel response selection. In Experiments 1 (DT:S group) and 2 (equal priority group), the SRT task was disrupted (i.e., mean RTs increased under dual-task conditions), and sequence learning was impaired. However, if it is parallel interfering response selection that disrupts sequence learning, then sequence learning should emerge under a dual-task situation that encourages serial central processes (as in the SRT priority group in Experiment 2). Furthermore, sequence learning should emerge even if this serial processing disrupts the performance of the SRT task.

We believe parallel interfering central processing is responsible for disrupting sequence learning because we used tasks with different input and output modalities in the present experiments. It remains possible, however, that effects on some precentral stage (e.g., changes in task preparation) may be responsible for the sequence-learning disruption in Experiments 1 and 2.

To control for this, we used a novel combination of the PRP procedure with a secondary SRT task in Experiment 3. With this design, a response-selection bottleneck should delay SRT task performance as SOA decreases (the typical PRP effect). That is, participants should suspend response selection for the SRT task while they select the response for the primary tone-identification task. If it is the sharing of processing capacity between primary and secondary tasks that disrupts sequence learning, then sequence learning should emerge for the secondary SRT task in Experiment 3. This is because the PRP procedure, under these conditions, likely induces a response-selection bottleneck on SRT task performance, which will cause response selection to proceed serially for the two tasks. Additionally, because the SRT task is secondary, participants should prepare for the primary tone-identification task on each trial. Thus, if sequence learning occurs, then this will suggest that a lack of preparation on the SRT task does not necessarily disrupt sequence learning and will strengthen our claim that differences in task preparation did not play a major role in the results from Experiments 1 and 2.

This procedure is novel in two ways. First, although similarities between the dual-task SRT and PRP procedures have been noted previously (Hsiao & Reber, 2001), to our knowledge, this is the first experiment in which sequence learning has been investigated using the PRP procedure. Second, it is the first experiment in which dual-task sequence learning has been investigated when the sequence occurs exclusively on the secondary task. Although other studies have modified the dual-task SRT procedure to include unique underlying sequences in both the primary and secondary tasks (e.g., Rah, Reber, & Hsiao, 2000; Schmidlk & Heuer, 1997), in Experiment 3, a sequence is included only in the secondary task; the task that should be primarily, if not wholly, affected by dual-task interference.

Method

Participants

Thirteen naïve undergraduates (ages 17–21, 8 men and 5 women) from the Georgia Institute of Technology participated in this experiment in partial fulfillment of a course requirement.

Stimuli and Apparatus

The stimuli, sequences, and apparatus were the same as in Experiment 1.

Design and Procedure

The SRT task. The SRT task was the same as in Experiment 1.

Tone-identification task. The tone-identification task was the same as in Experiment 1.

Trials. The trials were similar to Experiment 1 except that the tone stimulus preceded the visual stimulus by an SOA. The SOA varied equally and randomly across trials between 50, 125, or 200 ms. Only these relatively short SOAs were used to ensure that processing for the two tasks overlapped to some extent on all trials. Because the various SOAs occurred randomly, the sequence occurred across all three of them. All other aspects of the design and procedure were identical to the dual-task groups in Experiment 1.

Instructions and feedback. Participants were instructed to respond to the tone stimulus before responding to the visual stimulus and that failure to respond in that order was considered an error. These instructions were designed to encourage participants to adopt a central processing bottleneck even if graded capacity sharing is possible (cf. Tombu & Jolicœur, 2003). Participants were encouraged to respond as quickly and accurately as possible. As in Experiment 1, feedback was given at the end of each block.

Practice. Before the start of the experiment, participants completed five practice blocks. Practice Blocks 1–4 were identical to those single-task blocks used in the dual-task practice of Experiment 1. The 5th practice block was methodologically identical to the experimental blocks except the visual stimuli were unsequenced and only included 20 trials. RT and accuracy feedback followed each trial and appeared at the end of each block.

Explicit knowledge questionnaire. Follow-up questionnaires were identical to those used in Experiment 1.

Results

One participant reported pattern learning as a goal of the experiment and was removed from the analysis. All remaining participants performed at 90% or better on both tasks and were included in the analysis. We analyzed correct RTs and error rates from these participants separately for each task. We used a significance level of $p < .05$ for all inferential statistics. We used the Huynh-Feldt adjustment in every instance in which the assumption of sphericity was violated.
The PRP Effect

Figure 7 plots the mean SRT and tone-identification RTs for correct responses at each SOA from Blocks 1–11. We conducted two separate repeated measures ANOVAs, comparing mean RTs across the three SOAs for both the SRT and tone-identification tasks. For the SRT task, the test of sphericity was significant ($p < .05$), so we used the Huynh–Feldt adjustment. The effect of SOA was significant for the SRT task, $F(1.3, 14.6) = 675.75, p < .001$. This is the standard PRP effect. For the tone-identification task, the test of sphericity was not significant ($p = .23$). The main effect of SOA was also significant, $F(2, 22) = 35.22, p < .001$. Mean RTs for this task increased with SOA.

The SRT Task

RTs. We conducted a repeated measures ANOVA, with block (1–11) as a variable. The sphericity assumption was not violated ($p = .25$), and a significant main effect, $F(10, 110) = 10.50, p < .001$, was revealed. These data are plotted in Figure 8a. The transfer effect (comparing mean RTs from Blocks 11 and 13 with mean RTs from Block 12 combined across SOA) was significant, $t(11) = 1.99, p < .05$, one-tailed. These data indicate that participants learned the sequence. Furthermore, sequence knowledge in the SRT task was additive across SOAs when we compared the data from Block 12 with the data from Blocks 11 and 13 (see Figure 8b). The transfer effect was 26 ms, 25 ms, and 33 ms for the 50-ms, 125-ms, and 200-ms SOAs.

Error rates. Mean error rates were 3.0%. Participants were successfully able to respond to the tone-identification task before the SRT task as instructed, and mean out-of-order error rates were 0.03%. Again, we conducted an arcsine transformation and submitted it to a repeated measures ANOVA, with block (1–11) as a variable. A test of sphericity showed that the assumption of sphericity was violated for this analysis ($p < .001$), so we corrected the degrees of freedom. The main effect of block was significant, $F(4.0, 43.5) = 5.98, p < .01$. There was no transfer effect on mean error rates, $t(11) = 0.52, p = .61$.

Tone-Identification Task

RTs. We conducted a repeated measures ANOVA, with block (1–11) as a variable, and the sphericity assumption was violated ($p < .005$), so we adjusted the degrees of freedom. The ANOVA revealed a significant main effect of block, $F(1.9, 21.3) = 59.42, p < .001$ (see Figure 8a). Additionally, although some slowing on Block 12 is apparent, this transfer effect was not significant, $t(11) = 0.92, p = .19$.

Error rates. Mean error rates were 6.3%. We arcsine transformed data and submitted them to a repeated measures ANOVA, with block (1–11) as a variable. The test for sphericity was significant ($p = .05$), and we corrected the degrees of freedom. The main effect of block was not significant, $F(9.2, 110.1) = 1.32, p = .23$, nor was the transfer effect, $t(11) = 0.91, p = .38$, indicating that mean error rates were similar for Block 12 and Blocks 11 and 13.

Recognition

When we asked participants what they believed the purpose of the study to be, only 1 participant mentioned pattern learning and was removed from the analysis. The mean recognition score was 54.9% (SD = 10.3%). We calculated the $d'$ statistic for each group so as to control for response bias. These recognition questionnaire scores differed from chance, $t(11) = 2.2, p < .05$. This indicates that some of the participants had some explicit knowledge of the sequence.
Discussion

The PRP effect reported here, with tasks involving separate stimulus and response modalities, is indicative of serial central processing (Pashler, 1984, 1994a; Welford, 1959). Therefore, results from Experiment 3 (and the SRT priority group in Experiment 2) demonstrate that sequence learning can occur under a response-selection bottleneck. Additionally, the large PRP effect on the SRT task suggests that the cost of the dual-task overlap fell almost completely on the SRT task. Yet, significant sequence learning emerged. This is the first dual-task SRT study to dissociate dual-task performance from sequence learning (as done under single-task situations by Deroost & Soetens, 2006). That is, in all previous reports, sequence learning decreased under all dual-task conditions that also decreased SRT task performance (i.e., increased SRT task RT; see Figure 6). Here, however, we see a clear dissociation between SRT task performance and the learning of an underlying sequence. This suggests that only some kinds of central interference (viz., parallel central processing) disrupt sequence learning; other kinds (viz., central bottleneck) allow sequence learning to proceed unimpared.

The significant main effect of SOA in the tone-identification task is somewhat surprising given that the standard pattern of results is no effect of SOA on primary task RTs (see Pashler, 1994a). It suggests that participants were not always performing the tone-identification task independently of the SOA. Nevertheless, the PRP effect on the secondary SRT task replicates the standard pattern of dual-task interference in PRP experiments, suggesting that participants performed this experiment with the characteristic response-selection bottleneck. This is the critical finding in Experiment 3: Sequence learning occurred under a response-selection bottleneck even though the sequenced task was secondary.

If parallel interfering central processing disrupts sequence learning as we propose, then, because central processing occurred serially in Experiment 3, we would expect the amount of sequence learning to be similar across the SOAs. Figure 8b shows that this was indeed the case: Sequence learning occurred at all three SOAs. Interestingly, this learning effect was additive with SOA. Additivity suggests that sequence knowledge was not absorbed into the cognitive slack before the bottleneck, but rather affected processing after the bottleneck. This is consistent with the hypothesis that response selection mediates sequence learning (Deroost & Soetens, 2006; Hazeltine, 2002; Schwarb & Schumacher, 2009; Willingham et al., 1989) and further suggests that a lack of task preparation does not cause a disruption in sequence learning.

The present experiment cannot determine whether the amount of sequence learning during the first 11 blocks varied across the three SOAs. However, the SOAs occurred randomly, and the sequence spanned 12 trials; therefore, some learning must have occurred at all SOAs. Additionally, Experiment 2 showed that sequence learning depends on the organization of central processing, not the amount of task overlap. Therefore, we believe that the learning demonstrated in Experiment 3 is likely caused by serial central processing and not by the use of positive SOAs.

As a group, participants in Experiment 3 performed significantly greater than chance on the recognition questionnaire, demonstrating evidence for explicit sequence knowledge. It is reasonable to ask whether this overall increase in acquired explicit knowledge is sufficient to explain the results of Experiment 3. To investigate this question, we divided individual participants into two groups on the basis of their recognition questionnaire scores. We calculated transfer effects for the 7 participants who showed evidence of explicit knowledge (i.e., preformed above chance on the recognition questionnaire; mean transfer effect = 10 ms) and for the 6 participants with no explicit knowledge (i.e., performed at or below chance; mean transfer effect = 49 ms). The mean transfer effect was larger for the group that did not demonstrate explicit knowledge; therefore, the sequence-learning results from Experiment 3 were not driven by participants with explicit knowledge of the sequence.

General Discussion

Taken together, the results from these three experiments reveal that, under dual-task conditions, sequence learning is impaired only when parallel response selection for both tasks interfere with SRT task performance (Experiment 1 DT:S group and Experiment 2 equal priority group). When response-selection processes are performed serially, whether via the task delay produced by a long SOA (Experiment 1 DT:L group), task instructions to reduce interference (Experiment 2 SRT emphasis group), or when a dual-task procedure known to induce a serial processing bottleneck is used (Experiment 3), sequence learning proceeds normally—even when performance of the SRT task is substantially impaired (Experiment 3). In fact, the results from Experiment 3 dissociate dual-task performance and sequence learning, suggesting that it is the interference from two simultaneously active response-selection processes that disrupts sequence learning and not just the increased duration of the SRT task.

These results, outlining situations in which dual-task sequence learning is intact and situations in which it is impaired, offer a framework for understanding the controversies in the dual-task sequence-learning literature. It is likely that the ambiguity in the literature exists because previous studies have not controlled for central processing interference between the two tasks. Our results also have implications for theories for the underlying mechanisms of sequence learning as well as for theories for human information processing in multiple-task situations more generally. Furthermore, they provide direct evidence that parallel central processing (viz., Navon & Miller, 2002; Tombu & Jolicœur, 2003, 2005) can occur using a new dual-task procedure.

Implications for Theories of Dual-Task Sequence Learning

Our present findings are inconsistent with the general attentional resource hypothesis, which states that sequence learning is impaired in dual-task situations because the attentional resources necessary for successful learning are diverted from the primary to the secondary task (e.g., A. Cohen et al., 1990; Curran & Keele, 1993; Jiménez & Méndez, 1999; Nissen & Bullemer, 1987). This hypothesis predicts that when performing two tasks, interference will result and sequence learning will be impaired regardless of which mechanisms are shared (e.g., Curran & Keele, 1993; Jiménez & Méndez, 1999; Nissen & Bullemer, 1987). Here, however, we demonstrate successful sequence learning under several dual-task situations—even when the SRT task is secondary. As dis-
cussed previously and in more detail below, however, our results are consistent with a more specific version of this resource theory (viz., central capacity sharing; McLeod, 1977; Navon & Miller, 2002; Tombu & Jolicœur, 2003, 2005).

Our data also appear inconsistent with the automatic learning hypothesis (Frensch et al., 1998, 1999). Frensch and colleagues have proposed that sequence learning itself is not impaired in the dual-task SRT, but rather only the expression of sequence knowledge is affected by the addition of a secondary task. Results from Experiment 2 do not support this hypothesis. Participants in the equal priority group showed no evidence of sequence learning both during dual-task and the single-task conditions. These data suggest that sequence learning was disrupted in the dual-task condition—not just the expression of that knowledge. Similarly, the SRT priority group showed a pattern of results inconsistent with the predictions of the automatic learning hypothesis. Participants in this group showed evidence for successful sequence learning during both the dual-task and single-task phases of the experiment. Taken together, these findings demonstrate that transfer effects, and thus sequence learning, can be as large for dual-task as for single-task groups. Therefore, the expression of sequence knowledge need not be disrupted when two tasks are performed together.

Our present data also seem inconsistent with the organizational hypothesis of implicit sequence learning (Stadler, 1995). According to this theory, it is the variability in the processing requirements for the secondary task (e.g., update count for high but not low tones) that disrupts sequence learning. When secondary task processing is consistent across trials (as with the tone-identification task used here), the organizational hypothesis predicts that sequence learning should occur normally. Here, we demonstrate that dual-task processing disrupts sequences learning even with consistent secondary task processing. At least for our data, it is parallel response selection and shared capacity between the two tasks, and not intermittent processing, that affects sequence learning. Parallel interfering response selection, however, cannot explain Stadler’s (1995) single-task data demonstrating that randomly inserting pauses of variable lengths between sequenced trials disrupts sequence learning; therefore, there may, in fact, be a role for the organizational hypothesis in certain situations. However, several studies have failed to replicate the effect of varying RSI duration on sequence learning (Heuer & Schmidtke, 1996; Willingham et al., 1997), so the viability of the organizational hypothesis is unclear.

Additionally, our data also appear inconsistent with Schmidtke and Heuer’s (1997) task integration hypothesis and Keele and colleague’s (2003) two-system theory of sequence learning. Here, we repeatedly demonstrate that SRT task sequences can be learned in the presence of unsequenced tone-identification task trials (Experiment 1 DT:LT; Experiment 2 SRT priority; Experiment 3). Task instructions and task procedure affect SRT sequence learning, not the inability of learning systems to integrate visual and auditory stimuli.

Cognitive-Processing Locus of Sequence Learning

Finally, our data allow us to address the debate in the literature concerning the locus of learning in the SRT task. Theories implicate each of the three processing stages: stimulus encoding, response selection, and response execution, described previously. The present data highlight the role that response selection plays in dual-task sequence learning. The absence of sequence learning and the apparent dual-task interference on the SRT task when parallel central processing occurs, the reemergence of sequence learning when participants are encouraged to perform the SRT task first, and the additivity between sequence learning and SOA when the SRT is secondary in the PRP procedure are all consistent with theories implicating response selection as the locus for sequence learning (e.g., Deroost & Soetens, 2006; Hazeltine, 2002; Schwarb & Schumacher, 2009; Willingham et al., 1989).

We believe that response selection is the critical stage in sequence learning for a number of reasons. First, we used in the present experiments separate stimulus and response modalities to isolate the interference on the central processing stages of the two tasks. This decreased the likelihood that interference occurred at either stimulus encoding or response execution stages (Pashler & Johnston, 1998). Additionally, we used in Experiment 3 a procedure that, under the practice and instructional conditions used here, is widely believed to impose a response-selection bottleneck. Even while performing under this bottleneck, participants were able to learn the underlying sequence. This indicates that the benefit of having learned the sequence did not occur at a prebottleneck stage (i.e., general task preparation or stimulus encoding), as the effect was not absorbed into the cognitive slack.

The present research substantially constrains the possible theories for dual-task sequence learning and point to dual-task interference during parallel response selection as an important mechanism. More research is necessary before researchers can determine the mechanisms underlying why simultaneous response selection disrupts sequence learning. Yet, existing research allows us to offer some speculations. Some theories propose that response selection involves activating an appropriate response from task-relevant stimulus–response pairs stored in working memory (Curtis & D’Esposito, 2003; Miller & Cohen, 2001; Pashler, 1994c; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Schumacher, Cole, & D’Esposito, 2007). Selected stimulus–response pairs may remain active in working memory across trials. Learning processes may then identify cross-temporal contingencies in active stimulus–response pairs (N. J. Cohen & Eichenbaum, 1993; Frensch et al., 1994). Coactive stimulus–response pairs for distinct tasks, which occur during parallel response selection, may increase noise in the learning processes (Cleeremans & McClelland, 1991) or otherwise disrupt the coherence of the learning mechanisms (Keele et al., 2003). It is also possible that maintaining the elements of both tasks in memory limits the amount of time that the elements of the SRT task are available for these cross-trial contingencies to be formed (Frensch et al., 1994).

The dual-task disruption in sequence learning with parallel response selection is somewhat similar to performance decrements due to parallel response selection caused by cross-talk (i.e., when input intended for one task is incorrectly associated with the other task) between task stimulus–response pairs (Hazeltine, Ruthruff, & Remington, 2006; Hommel, 1998; Logan & Gordon, 2001). However, cross-talk is more typical in tasks with similar stimuli and/or response modalities. Tasks like the ones used here do not typically produce cross-talk (cf. Pashler, 1994a).

Whatever the mechanism is that reduces processing capacity for sequence learning, it seems to be specific to dual-task situations (parallel response selection, specifically). This is contrary to many
attentional resource theories, which postulate a more general mechanism (Kahneman, 1973; McLeod, 1977; Tombu & Jolicœur, 2003, 2005). A general reduction in central processing capacity allocated to sequence learning would predict that any factor that draws central capacity away from the sequence should disrupt sequence learning. However, as previously noted, increasing SRT task response-selection difficulty (e.g., Deroost & Soetens, 2006) or using more difficult secondary tasks (e.g., Heuer & Schmidtke, 1996) does not always impair spatial sequence learning.

**Implications for Theories of Multiple-Task Performance**

Our results also have implications for theories of multiple-task performance. The present results add to a growing literature suggesting that central processing can be shared under certain dual-task conditions. This idea had fallen out of favor in the past 25 years as the response-selection bottleneck hypothesis gained popularity. Evidence that response selection can be shared in a graded fashion between two tasks has implications for present models of multiple-task performance. Neither of two influential computational models of multiple-task performance (ACT-R/perceptual-motor [ACT-R/PM]; Byrne & Anderson, 2001; executive-process interactive control [EPIC]; Meyer & Kieras, 1997a; but see Logan & Gordon, 2001) includes a mechanism for graded sharing of central capacity. ACT-R/PM postulates a structural response-selection bottleneck under all conditions. EPIC allows for parallel response selection under some dual-task situations, but these simultaneous response-selection processes are independent of each other. The present data (see also Tombu & Jolicœur, 2005) supporting parallel interfering response-selection mechanisms suggest these models may have to be modified to encompass this organization of dual-task processing as well.

Still, the variety of ways in which people have been found to perform under multiple-task situations, response-selection bottleneck (for a review, see Meyer & Kieras, 1997a; Pashler, 1994a; Pashler & Johnston, 1998), parallel independent processing (e.g., Allport et al., 1972; Byrne & Anderson, 2001; Greenwald & Schulman, 1973; Hazeltine et al., 2002; Oberauer & Kliegl, 2004; Ruthruff et al., 2006; Schumacher et al., 2001; Shaffer, 1975), and graded capacity sharing (present data; McLeod, 1977; Navon & Miller, 2002; Tombu & Jolicœur, 2003, 2005) suggest to us that the basic idea outlined by Meyer and Kieras (1997a) in their EPIC architecture—that the allocation of processing is under participants’ strategic control—is likely correct.

Taken together, data from these three experiments demonstrate that the same two tasks can produce strikingly different dual-task results depending on relatively minor changes in the experimental procedure (variable SOAs; Experiment 1), task priority instructions (Experiment 2), and variable SOAs and task priority instructions (Experiment 3). Similar effects of the experimental procedure on dual-task processing have been reported previously (Schumacher et al., 2001, Experiments 1 and 2). In those experiments, individuals first participated in a dual-task experiment with a 0-SOA and equal priority instructions and then a PRP experiment (with monetary penalties for responding to the secondary task before the primary task). In the 0-SOA experiment, participants did not show any dual-task interference, whereas dual-task interference emerged in the PRP experiment. In the present studies, the PRP procedure produced dual-task interference and thus evidence for a bottleneck as well. The 0-SOA procedure used here, however, also produced dual-task interference under equal priority instructions and not the parallel independent response selection reported by Schumacher and colleagues (2001).

One reason for this discrepancy may be the difference in the amount of practice participants received in the two 0-SOA studies. Schumacher and colleague’s (2001) participants received considerably more practice than the participants in the present studies (over 800 additional trials and four additional experimental sessions). Additionally, we used simpler tasks in the present study than did Schumacher and colleagues. The relative ease of the tasks may be the reason that we found evidence for capacity sharing here where others have reported a bottleneck in similar situations (e.g., Pashler, 1994b; Ruthruff, Pashler, & Hazeltine, 2003). Nevertheless, the present data support the conclusions from Schumacher and colleagues that the PRP procedure may induce a bottleneck-processing strategy when it might not otherwise be necessary (but see Byrne & Anderson, 2001; Ruthruff, Johnston, Van Selst, Whitsett, & Remington, 2003; Tombu & Jolicœur, 2004).

**Conclusions**

Parallel interfering response selection seems to us to be a compelling organizing principle on which to explain the diverse set of multitask sequence-learning data, both in the literature and presented here. However, ruling out all potential alternate hypotheses (e.g., variable task preparation) is beyond the scope of the present data. Ultimately, more research will be necessary to distinguish between all possible competing theories. Nevertheless, the present data offer a set of conditions and experimental situations under which the interfering effects of dual-task processing on sequence learning may be studied fruitfully.

Finally, the present research has a number of real-world implications. As noted in the introduction, sequence learning plays an important role in our daily lives. As Lashley (1951) observed, the sequential ordering of movements is fundamental. Therefore, identifying why sequence learning sometimes fails is important to understanding human behavior. If researchers can better identify situations in which sequence learning is likely to be disrupted and the cause of this disruption, researchers may be able to develop training regimens to maximize the efficiency of learning sequences. Here, we have demonstrated the conditions under which sequence learning is impaired, namely, when parallel response selection for two tasks interfere.

This knowledge may have practical applications for many areas of instruction and performance. For example, ballroom dancers must constantly respond to auditory cues from their musical selection while simultaneously responding to somatosensory cues from their partner. Understanding how to time the monitoring for cues to maximize the efficiency of response selection may prove valuable both in practice and competition. Similarly, military pilots must continually react to verbal instructions while simultaneously monitoring and reacting to information presented on the visual displays in their cockpit. Failure to respond to any one of these cues may mean the difference between life and death. Understanding how to train pilots to organize these tasks so as to reduce central interference and maximize performance may thus be invaluable.
The study of dual-task sequence learning also has practical importance for understanding deficits in various psychological and neurological disorders as well. Understanding the mechanisms responsible for successful dual-task sequence learning in unimpaired individuals can provide useful insights into the deficits in clinical populations. These data have obvious applications to the study of Huntington’s disease (e.g., Kim et al., 2004), Parkinson’s disease (e.g., Smith & McDowall, 2004), and obsessive compulsive disorder (e.g., Kathmann, Ruppertseher, Hauke, & Zaudig, 2005), cases in which sequence learning is often impaired.

The data presented here provide a framework for understanding deficits in dual-task sequence learning both inside and outside the laboratory. Understanding the importance of organizing information processing during multiple-task performance to minimize the interfering effects of parallel central processing may prove essential for successful and efficient sequence learning.

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