The Absence of A Switch Cost When Preparing for Multiple Tasks: Interactions Between Element- and Ensemble-Level Effects

Mei-Ching Lien & Eric Ruthruff
NASA Ames Research Center

Six experiments examined an intriguing result from a dual-task study by De Jong (1995) where no task-switch cost was found. We investigated whether this phenomenon is due to the formation of task ensembles – a control structure covering more than one task element (e.g., prepare Task 1 and the switch to Task 2). Experiment 1, where tasks were performed individually, showed the usual large switch cost (182 ms). This cost disappeared and even reversed in Experiments 2-5, where the temporal and/or spatial contiguity between adjacent task elements was increased to encourage ensemble formation. In Experiment 6, the switch cost between elements was large within an ensemble, but small or nonexistent between ensembles. These data suggest that the element-level effect is fragile and can be reduced or eliminated when a higher-level control structure is formed. A dual-route model of task switching is proposed.

In the course of daily activities, people face myriad tasks that could potentially be performed. Consequently, the key to achieving one's goals is the ability to select, prepare, and perform the most relevant task(s), rather than simply repeat the last task or respond in a reflexive, bottom up manner to the most salient impending stimuli. Top-down task selection is one important function of executive control. Another main function of executive control is the coordination of processes for different tasks being carried out in close temporal synchrony. Because executive control plays an important role in human performance, it has occupied an increasingly prominent position in recent cognitive psychology research.

One approach to understanding executive control is to study the mental processes involved in task switching. In the task-switching paradigm, tasks are presented in a series of single-task trials, where each task is a repetition or a switch from the previous one. Mean response time (RT) is generally longer for task switches than for task repetitions (the *switch cost*), even when participants have sufficient time to prepare to switch tasks (the *residual switch cost*). Rogers and Monsell (1995) proposed that the residual switch cost is due to the need for on-line reconfiguration when the task switches. Yet, an incidental result from a dual-task study with variable task order (De Jong, 1995) suggests that task switching does not always produce a cost. This tentative but intriguing finding, if genuine, would have implications to existing task-switching theories. One factor in De Jong's study that might enable elimination of the switch cost is the formation of hierarchical task organizations. We systematically investigated this possibility and showed that the switch cost, which normally is very robust, fails to occur under some circumstances. We propose a model of task switching to account for these findings.

Background on Task Switching

In 1927, Jersild published a seminal study on the costs of task switching. In his study, participants performed speeded choice RT tasks in alternating task blocks (e.g., ABAB…) and pure task blocks (e.g., AAAA…or BBBB...). Jersild found that responses were slower in the alternating task block than in the pure task block (i.e., the switch cost). Subsequent studies have confirmed Jersild's main findings using modern experimental methodology and a range of different tasks (e.g., Allport, Styles, & Hsieh, 1994; Spector & Biederman, 1976). Another important finding from Jersild's study is that switch costs are especially large when the tasks operate upon a common stimulus domain (e.g., odd/even judgments versus greater/less than judgments on digits). Because each stimulus is associated with, or "affords" the performance of two tasks[1] in this case, the stimulus might automatically activate both the appropriate and inappropriate task sets. Consequently, more time might be needed to inhibit activation of the inappropriate task in this "dual-affordance" condition than in the single-affordance condition where each stimulus is associated with only one relevant task.

Using a variant of Jersild's method, Allport et al. (1994) presented empirical evidence that switch costs are due to *task set inertia* – the involuntary carryover of response activation from one task element to the next task element[2]. Such persisting activation, not under participants' control, would facilitate performance when the task repeats but interfere when the task switches (see also Allport & Wylie, 2000). Because task-set activation is presumed to passively decay over time, the task set inertia hypothesis implies that switch costs should be reduced when the time interval between each response and subsequent stimulus onset (response-stimulus interval; RSI) increases. Although increasing the RSI does reduce switch costs, Meiran (1996, 2000) argued persuasively that the RSI effect reflects an active preparation process rather than a passive decay of task-set activation.

Rogers and Monsell (1995) noted a major drawback of Jersild's (1927) experimental design, and that of Allport et al. (1994), which is that switches and repetitions are performed in separate blocks of trials. Participants, therefore, must keep two tasks available in alternating blocks, but only one task in pure blocks. Consequently, the costs of task switching are confounded with the costs of holding two stimulus-response (S-R) mappings in mind (see Strayer & Kramer, 1994, for a similar argument regarding consistent and varied mappings in a memory search task). To avoid this confound, Rogers and Monsell used an alternating-runs paradigm, in which task switches and task repetitions were intermixed within the same block. For instance, Task A and Task B could be presented in the sequence AABBAABB, etc. In their experiments, two different visual-manual keypress tasks were used. One task was to classify a digit as odd (digits 3, 5, 7, and 9) or even (digits 2, 4, 6, and 8) and the other task was to classify a letter as consonant (letters G, K, M, and R) or vowel (letters A, E, I, and U). In most of their experiments, a dual-affordance condition was used, in which a digit and a letter were displayed adjacently on the screen. To assist participants in tracking which task needed to be performed on these stimuli, they were presented in one of 4 squares, with the top two squares indicating one task and the bottom two squares indicating the other task. On each trial, the stimuli were displayed in the square located immediately clockwise from the square used in previous trial. Therefore, in addition to the repeating task sequence, the stimulus location provided a cue as to which task should be performed.

Using the alternating-runs paradigm, Rogers and Monsell (1995) confirmed the existence of a substantial switch cost of approximately 200 ms with dual-affordance tasks (Experiments 2-3). Importantly, they also showed that switch costs remain large even when participants have plenty of time to prepare for the upcoming task switch (e.g., a long RSI of 1,200 ms). This residual switch cost led Rogers and Monsell to argue that on-line task reconfiguration is needed when the task switches, but not when it repeats. A crucial feature of their on-line reconfiguration hypothesis is that the stimulus is needed to trigger completion of the reconfiguration. As described in their General Discussion, "this is the completion of a stagelike process of reconfiguration and that completion can be triggered only exogenously by the arrival of a stimulus suitably associated with the task" (p. 229). Logan and Gordon (2001) proposed a more specific quantitative model along these same lines, suggesting that a set of parameters for a new task must be transmitted from working memory to the subordinate processor when the task switches but not when it repeats.

Another piece of evidence supporting the on-line reconfiguration hypothesis comes from Rogers and Monsell's (1995) Experiment 6, in which the repeating task sequence AAAABBBB was used. The first element within each run of the same task type was a task switch, whereas the second, third, and fourth elements were task repetitions. Mean RT was approximately 230 ms slower and the error rate was 3% higher for the first element of each run (a task switch) than the second element of each run (a task repetition). Importantly, no differences were found between the second, third, and fourth elements of each run (all of which were task repetitions). Gopher, Armony, and Greenshpan (2000) also found that a switch cost occurred on the first element following a task switch but not on the subsequent elements within a run. In addition, they observed a cost on the first task element following a change in task emphasis (i.e., from speed to accuracy stress or vice versa), even though the task type repeated (e.g., the digit value task). This finding strongly suggests that task performance depends primarily on whether the task is same or different (in terms of S-R mapping rules or task emphasis) from the one performed in the immediately preceding element. Interestingly, the benefit of repeating the operations performed on the previous task element has been found to be just as large when participants do not expect the task to repeat as when they do expect it to repeat (e.g., Lien, Schweickert, & Proctor, 2002; Ruthruff, Remington, & Johnston, 2001; Sohn & Carlson, 2000).

De Jong's (1995) Dual-Task Study

Contrary to traditional task-switching theories, an incidental result in De Jong's (1995) study suggests that changing the cognitive operations from one task element to the next might not always produce a switch cost. De Jong was interested in the nature of preparatory control and how central attention is allocated to two temporally overlapping tasks. Accordingly, he adopted a psychological refractory period (PRP) paradigm in which two different tasks (Task 1 and Task 2) were presented with a variable stimulus onset asynchrony (SOA). A typical finding from this paradigm is that RT for Task 2 is much longer when the SOA is short than when it is long (called the PRP effect; e.g., Pashler, 1984; Welford, 1952). Recent evidence suggests that the PRP effect is primarily due to the inability to perform central processes on two tasks at a time (for reviews, see Lien & Proctor, 2002; Pashler & Johnston, 1998; but see also Navon & Miller, 2002 for an opposing view).

De Jong (1995) presented a visual-manual task and an auditory-vocal task, with a variable task order from trial to trial. In Experiment 1, the validity of a task-order cue for each trial was manipulated. De Jong hypothesized that if central attention is not committed to either task prior to stimulus onset, then tasks should be handled on a first-come, first-served basis. Thus, participants should generally respond to the two tasks in the order in which they were presented, both for valid and invalid cue conditions. In contrast, if central attention is prepared for the task cued to come first, then central attention will need to be switched in the case of an invalid cue. If the second task arrives before the switch of central attention can be completed (e.g., at short SOAs), it might be performed first (called a response-order reversal). De Jong found that the frequency of reversals was in fact much higher in the invalid cue condition than in the valid cue condition, indicating that prior to stimulus onset participants prepared only the task that was cued to be presented first. In Experiment 2, where there were no explicit task-order cues, De Jong still found a strong bias to perform the two tasks in a particular order, namely the order used in the previous trial. He concluded that, "the preparatory state at the start of a trial appeared to be biased not towards the task performed last on the previous trial but towards performing the two tasks in the same order as that on the previous trial" (p. 15).

Experiments 1 and 2 of De Jong (1995) demonstrated that participants prepare for the task expected to come first. Experiment 3 addressed whether the subsequent switch to Task 2 can also be explicitly prepared prior to the completion of Task 1. Tasks were presented in fixed-order blocks (e.g., Task A and Task B in the order of AB-AB-AB-AB…) and alternating-order blocks (e.g., AB-BA-AB-BA…). The logic of Experiment 3 was that if the subsequent switch to Task 2 can be prepared prior to the completion of Task 1, then the processing of Task 2 should take less time in the fixed-order condition than in the alternating-order condition. That is because the control structure (e. g., prepare Task A and the subsequent switch to Task B) stays the same throughout the fixed-order condition, but the control structure must change on every trial in the alternating-order condition. In contrast, if the switch to Task 2 must wait until the completion of Task 1, performance on Task 2 should be equivalent in both the fixed-order and alternating-order conditions. De Jong found that RT2 indeed was slower in the alternating-order condition than in the fixed-order condition. Putting these findings together, he concluded that in the overlapping tasks paradigm, participants prepare in advance (prior to the onset of stimulus for Task 1) for both the task expected to come first and the subsequent switch to the other task.

One interesting but neglected result in De Jong's (1995) Experiment 3, which may have implications for traditional task-switching theories, is that RT on Task 1 was significantly (albeit only slightly – 11 ms) slower in the alternating-order condition (e.g., AB-BA-AB-BA…) than in the fixed-order condition (e.g., AB-AB-AB-AB…). In other words, responses to Task 1 were faster when it was a switch from the previous Task 2 than when it was a repetition. This intriguing "switch benefit"[3] at the level of the task element is opposite to the usual finding from traditional task-switching studies using single-task trials. De Jong, who focused more on the Task 2 data rather than the Task 1 data, did not comment on this unusual finding. He merely noted that, "subjects were able to prepare for the first task during the ITI [inter-trial interval] in the alternating-order condition, as indicated by the fact that responses to S1 [stimuli for the first task] in this condition were only slightly slower than those in the fixed-order condition" (p. 20).

Element-Level and Ensemble-Level Effects

The empirical switch benefit found by De Jong (1995), if genuine, has several interesting implications for task switching theory. At an empirical level, it suggests that task performance depends more on whether the preparatory states (i.e., what De Jong called the control structure for Task 1 and Task 2 in each trial) switch or repeat than on whether the cognitive operations switch or repeat. That is because Task 1 responses were faster in the fixed-order condition (AB-AB) – where the preparatory state repeated but the task switched – than in the alternating-order condition (AB-BA) – where the preparatory state switched but the task repeated. For the ease of the discussion, we refer to the task elements (e.g., Task 1 and Task 2) covered by this preparatory control structure as a *task ensemble* (or *an ensemble of task elements*).

At a theoretical level, De Jong's (1995) data suggest that some modification to traditional task-switching theory is needed. Perhaps the simplest modification is to propose that the switch in cognitive operations does result in a substantial cost (*an element-level effect*) on Task 1 of the fixed-order blocks (AB-AB), but this cost is counteracted by an even larger benefit of repeating the ensemble (*an ensemble-level effect*). In other words, element-level and ensemble-level effects might contribute roughly additively to task performance. A more extreme proposal is that there is no cost of switching between cognitive operations, at least not in the context of Task 1 in De Jong's dual-task design. For instance, the benefit of repeating a task at the element level might be very fragile, disappearing whenever the preparatory state for the task ensemble changes. These possibilities and others will be examined in the General Discussion.

Although it is tempting to attribute the empirical switch benefit in De Jong's (1995; Experiment 3) study to the formation of task ensembles, there are several reasons why his results are not conclusive. First, a switch benefit was found in only one experiment and therefore needs to be replicated. More importantly, the absence of a switch cost may due to factors other than the formation of an ensemble. For instance, it might due to the use of single-affordance tasks, which often produce little or no switch cost (e.g., Jersild, 1927; Spector & Biederman, 1976), combined with a larger than usual amount of practice (3 sessions of 720 trials each). Furthermore, different input modalities (visual and auditory) were used for the two tasks in De Jong's study, whereas only one input modality (visual) is used for both tasks in traditional task-switching studies (e.g., Allport et al., 1994; Rogers & Monsell, 1995). The separation of input modalities might minimize the cost of task switching. Given these considerations, it is plausible that De Jong's design would have produced no switch cost even without ensemble formation. It is difficult to assess this possibility because he did not include a control condition in which task elements within a trial (Task 1 and Task 2) were performed independently (i.e., in which an ensemble was not formed), as in the traditional task-switching paradigm. Another complicating factor in De Jong's study is the presence of temporal overlap between Task 1 and Task 2. Perhaps Task 1 was differentially influenced by temporal overlap in the fixed- and alternating-order conditions. These problems stem from the fact that De Jong did not initially intend to study the switch benefit on Task 1, nor did he follow up on this finding. Clearly, further research is needed to determine whether ensemble formation does in fact reduce the switch cost relative to an appropriate control condition.

The Purpose of the Present Study

In the present study, we examined under what conditions the switch cost can be eliminated or reversed, and considered several different theoretical explanations. Although De Jong (1995) used an overlapping task paradigm, task overlap might not be a key ingredient and it complicates comparisons with traditional task-switching experiments; therefore, we presented only non-overlapping, single-task trials in all experiments. Following De Jong, tasks were presented in either a fixed order (e.g., AB-AB) or an alternating order (e.g., AB-BA).

To evaluate the effect of ensemble formation, it was necessary to first measure the baseline switch cost when tasks are performed independently. Thus, Experiment 1 used a variant of the traditional task-switching paradigm with a long, constant RSI (1,500 ms) between each task element. We used dual-affordance tasks performed on digit stimuli (greater or less than 5 for the magnitude task and odd or even for the category task), because they generally produce large switch costs (150-200 ms). The elimination of these large switch costs in subsequent experiments, if it occurs, would be very impressive and easy to detect.

A secondary goal of this study was to determine what factors, if any, lead to the formation of ensembles and the elimination of the switch cost. One reason that participants might form task ensembles is to simplify their mental organization of the task element sequence (similar to the concept of *chunking* in the memory literature). As a concrete example, it might be easier to represent a sequence such as ABABAB as a repetition of task ensembles (i.e., AB-AB-AB) rather than as an alternation of task elements (i.e., A-B-A-B-A-B). In addition, participants are likely to group two adjacent task elements that are presented in close together in time or close together in physical space (just as early Gestalt psychologists proposed that visual objects are organized into groups based on their spatial and temporal arrangement). In Experiment 2, we investigated the possibility that temporal contiguity was sufficient to produce an ensemble effect. Therefore, we merely reduced the RSI between two adjacent task elements (which we call Task 1 and Task 2) from 1,500 ms to 300 ms. In Experiments 3 to 5, we added spatial contiguity to the displays; specifically, Task 1 and Task 2 appeared within a common frame (a semi-circle).

Because the switch cost decreased and even reversed when Task 1 and Task 2 were presented in close temporal and spatial contiguity (Experiments 4 and 5), the final goal was to see if the element-level switch effect had been eliminated, or whether it was still present but was negated by an even larger ensemble effect working in the opposite direction. Because the design of Experiments 2 to 5 confounded element-level effects with ensemble-level effects, Experiment 6 used a slightly different paradigm where the ensemble always repeated but the elements could be either a task switch or a task repetition. Thus, it was possible to measure the element-level switch cost in isolation, holding constant any effect of ensemble switching.

Overview of Task Paradigm

Experiments 1 to 5 measured the switch cost in the same way as in De Jong (1995, Experiment 3), but using a task presentation similar to that of traditional task-switching studies (e.g., with no temporal overlap)[4]. On each trial, participant performed the magnitude task (Task A) and the category task (Task B) in one of the two possible orders (AB or BA). We refer to the first and second element in each trial as Task 1 and Task 2, respectively. The task order was either fixed within a block (e.g., AB-AB-AB…) or alternating (e.g., AB-BA-AB…).

In both the fixed- and alternating-order conditions, Task 2 was always a switch from Task 1. However, Task 1 was an element-level repetition from Task 2 of the previous trial in the alternating-order condition, but was an element-level switch in the fixed-order condition. Accordingly, the switch cost on Task 1 was measured by subtracting Task 1 RT in alternating-order blocks (element-level task repetitions) from that obtained in fixed-order blocks (element-level task switches). The switch cost on Task 1 error rate was measured in a similar way.

Because the digit stimulus itself does not indicate which task should be performed, we provided two redundant task cues, as in Rogers and Monsell (1995). One cue was the predictable, repeating task sequence, which was constant throughout each block. The other cue was the color of the location in which the stimulus appeared. The stimulus frame defining the possible locations was a circular (Experiments 1 and 2) or a semi-circular object (Experiments 3 to 5), divided into quadrants (like slices of a pizza; see Figure 1). Black quadrants indicated the magnitude task and blue quadrants indicated the category task. The stimuli rotated from quadrant to quadrant in a predictable manner (generally clockwise) between trials.

Experiment 1

The purpose of Experiment 1 was to measure the baseline element-level switch cost. A circular frame with four quadrants was presented in the center of the screen throughout each block. The first stimulus of each block was presented in the top quadrant (see Figure 1). The subsequent stimuli were presented, with a constant RSI of 1,500 ms, in the quadrant located immediately clockwise from the previous one, similar to the procedure used by Rogers and Monsell (1995). Given this long and constant RSI, participants were likely to prepare task elements individually.

Method

Participants. Sixteen participants, ranging in age from 17 to 23 years, from colleges and universities surrounding the National Aeronautics and Space Administration (NASA) Ames Research Center participated in partial fulfillment of course requirements. All participants were required to have normal or corrected-to-normal vision.

Apparatus and stimuli. The stimuli were presented on IBM-compatible microcomputers connected to SONY Trinitron monitors, housed in a dedicated, sound-attenuating booth. Stimulus presentation, timing, and data collection were controlled using E-Prime software. The circular object was 8 cm in diameter and was divided into 4 quadrants (see Figure 1): Top, Right, Bottom, and Left Quadrants. The stimuli were the digits 1 to 9, excluding 5, presented in the center of each quadrant (about 2 cm from the middle of the circle). The digit was 0.6 cm in width and 1.0 cm in height. Based on a viewing distance of approximately 55 cm, each digit subtended approximately 0.63^{o} width x 1.04^{o} height.

Design and procedure. Two different numerical judgments, magnitude and category, were used as tasks. For the magnitude task (Task A), participants determined whether the number was greater or less than 5. They were to press the “z” key with their left-index finger if the number was less than 5 (1, 2, 3, or 4) and to press the “/” key with their right-index finger if the number was greater than 5 (6, 7, 8, or 9). For the category task (Task B), participants judged whether the number was odd or even. They were to press the “z” key with their left-index finger if the number was odd (1, 3, 7, or 9) and to press the "/" key with their right-index finger if the number was even (2, 4, 6 or 8).

The four quadrants were colored blue or black to indicate the task to be performed on stimuli in that quadrant. The black color indicated that the magnitude task should be performed, whereas the blue color indicated that the category task should be performed. The first stimulus of each block appeared in the Top Quadrant. After participants responded to that digit, feedback ('wrong' on error trials, a blank message on correct trials) appeared in that quadrant for 300 ms. A new digit appeared 1,200 ms later in the quadrant located immediately clockwise (Right Quadrant) from the previous digit. Thus, the total RSI was 1,500 ms. Figure 1 shows a sequence of events for stimuli presented in the Top and Right Quadrants, using the AB-AB task sequence as an example. The digits continued rotating clockwise around the circle throughout the block (i.e., through the Top, Right, Bottom, Left Quadrants and back to the Top Quadrant, etc.). Therefore, the distance from one stimulus to the next was constant, as in Rogers and Monsell's (1995) stimulus display. Another consequence of this procedure is that the color for a quadrant was constant throughout each block but changed across blocks, depending on the specific task sequence to be performed.

Although there was no reason to form an ensemble of Task 1 and Task 2 in Experiment 1, for continuity with the subsequent experiments we refer to task sequences of ABAB and BABA as the fixed-order condition and task sequences of ABBA and BAAB as the alternating-order condition. Participants performed each of the four block types once within the session. Block type was constrained to alternate between fixed-order sequences (ABAB/BABA) and alternating-order sequences (ABBA/BAAB). Consequently, there were four possible orders of block types in a session: (1) ABAB, ABBA, BAAB, then BABA, (2) ABBA, ABAB, BABA, then BAAB, (3) BAAB, BABA, ABAB, then ABBA, or (4) BABA, BAAB, ABBA, then ABAB. Each participant was randomly assigned one of these four orders, with the restriction that each order be used equally often across participants.

Participants first performed 64 practice trials, which served to acquaint them with the tasks and the paradigm. For each of the 4 block types, participants performed a practice block of 32 trials (to acquaint them with the new task sequence) followed by four blocks of 64 regular trials each. The experiment lasted approximately 30 minutes. Participants were told that speed and accuracy of responding were both very important. They were also encouraged to take a brief break between blocks.

Results and Discussion

The first cycle of four tasks in each experimental block, serving as warm-up trials, were omitted. Also omitted were task elements where stimuli repeated, to avoid contamination from stimulus repetition effects. Only correct responses with RT greater than 100 ms and less than 2,000 ms were included in the RT data. Approximately 3% of the trials were omitted in this data analysis because they fell outside these cutoffs[5]. RT for each task was computed only for trials when the current and previous responses were correct, whereas the proportion of error (PE) was computed for each task regardless of whether the previous response was correct.

Mean RT and PE for the four tasks in each cycle (Task 1, Task 2, Task 1, Task 2) are shown in Table 1 for each block type. Task type, magnitude (Task A) versus category (Task B) had little effect in these experiments and did not consistently interact with other factors; consequently, task type was not included as a factor in the final data analyses. Because Task 2 was always an element-level task switch, the performance on Task 2 cannot be used to test our main hypotheses. Thus, only data analyses on Task 1 were reported. An alpha level of .05 was used to determine statistical significance.

The main purpose of Experiment 1 was to provide a baseline for the element-level switch cost. This switch cost was measured by comparing Task 1 in the fixed-order condition (e.g., ABAB; element-level task switch) to Task 1 in the alternating-order condition (e.g., ABBA; element-level task repetition). Thus, RT and PE on Task 1 were analyzed as a function of task order condition (fixed and alternating). The effect of task order condition on RT was significant, $F(1, 15) = 31.41$, $p < .001$, $MSE = 16{,}927$. Mean RT for Task 1 was 624 ms in the alternating-order condition but was 807 ms in the fixed-order condition. In other words, participants responded to Task 1 approximately 182 ms faster when it was a task repetition than when it was a task switch. The effect was not significant in the PE analysis.

The 182-ms element-level switch cost obtained in this experiment is consistent with the findings of traditional task-switching studies (e.g., Rogers & Monsell, 1995). Because a constant RSI was used in Experiment 1 (but not in the subsequent experiments), a different way of measuring switch costs is to compare the performance on task repetitions (Task 1) and task switches (Task 2) within the alternating-order condition (e.g., ABBA) only. Using this measure, which is the one used by Rogers and Monsell, we obtained a 151-ms switch cost. This switch cost is similar to the effect obtained with the dual-affordance tasks in their study, and is similar to the 182-ms switch cost we obtained by comparing Task 1 performance in the fixed-order and alternating-order conditions.

Experiment 2

The purpose of Experiment 2 was to determine if responses to Task 1 would still be faster in the alternating-order condition (e.g., AB-BA) than in the fixed-order condition (e.g., AB-AB) when an ensemble of Task 1 and Task 2 was formed. In De Jong's (1995) Experiment 3, the stimulus for Task 2 appeared while participants were still performing Task 1. The temporal proximity between Task 1 and Task 2 might have increased the likelihood of these two tasks forming an ensemble. Therefore, in our Experiment 2, as an initial attempt, we simply shortened the RSI between Task 1 and Task 2 to 300 ms while leaving the RSI between trials (i.e., from Task 2 of the previous trial to Task 1 of the next trial) at 1,500 ms (see Figure 2). This modification brought us closer to the PRP paradigm used in De Jong's Experiment 3. However, in our design the stimulus for Task 2 did not appear until after participants had responded to Task 1, as in traditional task-switching studies. Thus, unlike De Jong (1995), there was no temporal overlap in the processing of Task 1 and Task 2.

In our paradigm, we measure switch costs by comparing the performance on Task 1 between the fixed-order and alternating-order conditions. Therefore, even though we shortened the RSI between Task 1 and Task 2 in Experiment 2, the immediate events leading up to the critical task (Task 1) were exactly the same as in Experiment 1. If task performance primarily depends upon whether the cognitive operation switches or repeats from one element to the next, the Task 1 switch cost should be similar to that obtained in Experiment 1. In other words, Task 1 RT should still be faster in the alternating-order condition than in the fixed-order condition.

Method

Participants. There were 16 participants in this experiment. They were students from the same participant pool as in the previous experiment, but none had participated in that experiment. All participants were required to have normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1 with the only change being that the RSI between Task 1 and Task 2 was reduced from 1,500 ms to 300 ms, just enough time for the presentation of the Task 1 feedback message.

Results and Discussion

Mean RT and PE for the four tasks in each cycle (Task 1, Task 2, Task 1, Task 2) are shown in Table 1. The data analyses were performed in the same way as in Experiment 1. Approximately 5% of the trials were omitted because of RT cutoffs. The effect of task order condition on Task 1 was significant for RT, $F(1, 15) = 9.71$, $p < .01$, $MSE = 23,715$, but not for PE, $F(1, 15) < 1.0$. Mean RT for Task 1 was 841 ms in the alternating-order condition (e.g., AB-BA) but was 961 ms in the fixed-order condition (e.g., AB-AB). In other words, participants responded 120 ms faster to Task 1 when it was a task repetition than when it was a task switch.

When we shortened the RSI between Task 1 and Task 2, the element-level switch cost on Task 1 was reduced from 182 ms in Experiment 1 to 120 ms in Experiment 2. However, a comparison of switch costs between Experiment 1 and Experiment 2, including the variable of experiment, did not show a significant two-way interaction of experiment and task order condition for RT, $F(1, 30) = 1.53$, $p > .05$, $MSE = 20,321$, and for PE, $F(1, 30) < 1.0$. Although it was not significant, the switch-cost reduction is consistent with the hypothesis that ensemble formation influences the switch cost on Task 1.

Experiment 3

In Experiment 2, increasing the temporal contiguity between Task 1 and Task 2 reduced the switch cost, albeit non-significantly, relative to Experiment 1. However, unlike De Jong's (1995) Experiment 3, a switch cost was still obtained. One potential reason for the difference in results is that temporal contiguity failed to produce an ensemble of Task 1 and Task 2. Perhaps the 300-ms RSI could not easily be distinguished from the 1,500-ms RSI or perhaps participants had difficulty tracking which task elements had a short preparation time (short RSI) and which ones had a long preparation time (long RSI). Consequently, participants might not have formed an ensemble of Task 1 and Task 2. Moreover, if participants did not know in advance that they would have a sufficiently long preparation time, they might have failed to engage in the appropriate preparation for the upcoming task element (see Rogers & Monsell, 1995, for a similar argument). One line of evidence for this possibility is that responses on Task 1 and Task 2 were, overall, much slower in Experiment 2 than in Experiment 1 (see Table 1).

Besides the temporal dimension, spatial location is one of the most salient physical dimensions in perception. Research on Gestalt Organizational Principles has shown that objects are optimally grouped as a unit when they are connected and located within the same explicit boundary on the display. These methods of grouping are known as connectedness and common region, respectively (Rock & Palmer, 1990). Hence, Experiment 3 examined the switch cost, relative to that in Experiment 1, with both temporal contiguity and spatial contiguity between Task 1 and Task 2. Therefore, instead of presenting all 4 quadrants of the circular frame at all times (as in the previous two experiments), a semi-circular frame containing only the 2 quadrants for the current ensemble was presented in Experiment 3 (see Figure 2). The RSI between Task 1 and Task 2 was still 300 ms, as in Experiment 2.

Method

Participants. There were 16 participants in this experiment. They were students from the same participant pool as in the previous two experiments, but none had participated in those experiments. All participants were required to have normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure were the same as in Experiment 2, except as noted. Only two quadrants of the semi-circular frame appeared on the screen in each trial (i.e., Top and Right Quadrants appeared first, then Bottom and Left Quadrants, then back to Top and Right Quadrants; see Figure 2). After participants responded to Task 2, feedback for Task 2 was displayed inside the quadrants for 300 ms. The feedback and the semi-circular frame disappeared, then, the frame for the next two quadrants appeared. After 1,200 ms, the stimulus for Task 1 appeared. Therefore, similar to the previous two experiments, the total RSI leading up to Task 1 was remained 1,500 ms.

Results and Discussion

Mean RT and PE for the four tasks in each cycle (Task 1, Task 2, Task 1, Task 2) are shown in Table 1. The data analyses were performed in the same way as in the previous two experiments. Approximately 4% of the trials were omitted because of the RT cutoffs. The effect of task order condition on Task 1 was not significant for RT, $F(1, 15) = 2.51$, $p > .05$, $MSE = 16{,}420$, and for PE, $F(1, 15) = 2.29$, $p > .05$, $MSE = 0.0009$. Mean RT for Task 1 was 857 ms in the alternating-order condition (e.g., AB-BA) and was 908 ms in the fixed-order condition (e.g., AB-AB). Participants committed only .012 more errors in alternating-order condition than in the fixed-order condition. In order words, participants responded to Task 1 slightly faster (51 ms) but with slightly more errors when that task element repeated than when it switched from Task 2 of the previous trial.

Although the RSI leading up to Task 1 was unchanged from Experiments 1 to 3, the switch cost was reduced from 182 ms in Experiment 1 and 120 ms in Experiment 2 to only 51 ms in Experiment 3 (see Figure 3). In other words, the switch cost is less than one-third of its original size. A comparison of switch costs between Experiment 1 and Experiment 3, including the variable of experiment, showed a significant two-way interaction of experiment and task order condition for RT, $F(1, 30) = 8.30$, $p < .01$, $MSE = 16{,}674$, and for PE, $F(1, 30) = 5.63$, $p < .05$, $MSE = 0.0009$. Thus, the temporal and spatial contiguity between Task 1 and Task 2 appears to have dramatically reduced the element-level switch effect.

Experiment 4

In the previous three experiments, Task 1 and Task 2 in the fixed-order condition (e.g., AB-AB) were presented clockwise in a circular or semi-circular frame. The first ensemble of Task 1 and Task 2 was presented in the Top and Right Quadrants but the second ensemble of Task 1 and Task 2 was on the Bottom and Left Quadrants (see Figure 2). Even though the ensemble repeated, the position for the ensemble always changed from one trial to the next. This presentation may have prevented recognition that the ensemble was repeated. To avoid this problem, we presented a particular ensemble of Task 1 and Task 2 in the same position on every trial in Experiment 4. If the consistent representation from trial to trial can enhance recognition that an ensemble of Task 1 and Task 2 repeated, an even stronger ensemble-level effect on the switch cost should be obtained.

Method

Participants. There were 16 participants in this experiment. They were students from the same participant pool as in the previous experiments, but none had participated in those experiments. All participants were required to have normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure were the same as in Experiment 3, except as noted. The Top and Right Quadrants were always colored black and blue, respectively, to indicate the sequence of Task A (the magnitude task) followed by Task B (the category task). The Bottom and Left Quadrants were always colored blue and black, respectively, to indicate the sequence of Task B followed by Task A.

In the AB-AB sequence of the fixed-order condition, Task A always appeared in the Top Quadrant and Task B always in the Right Quadrant. Thus, the task presentation for this sequence was Top Quadrant, Right Quadrant, then Top Quadrant, Right Quadrant, and so on. In the BA-BA sequence, Task B always appeared in the Bottom Quadrant and Task A always in the Left Quadrant. Thus, the task presentation for this sequence was Bottom Quadrant, Left Quadrant, then Bottom Quadrant, Left Quadrant, and so on. In the alternating-order condition, the presentation of the AB-BA sequence was Top Quadrant, Right Quadrant, then Bottom Quadrant, Left Quadrant, and so on. The presentation of the BA-AB sequence was similar to the AB-BA sequence except that the first stimulus appeared in the Bottom Quadrant, then rotated in a clockwise direction. The presentation time and RSI were the same as those in Experiment 3.

Results and Discussion

Mean RT and PE for the four tasks in each cycle are shown in Table 1. The data analyses were performed in the same way as in the previous experiments. Approximately 4% of the trials were omitted because of the RT cutoffs. The effect of task order condition on Task 1 was significant for RT, $F(1, 15) = 6.13$, $p < .05$, $MSE = 11{,}719$, but not for PE, $F(1, 15) < 1.0$. Mean RT for Task 1 was 932 ms in the alternating-order condition (e.g., AB-BA) but was only 865 ms in the fixed-order condition (e.g., AB-AB). Thus, in contrast to the previous three experiments, mean RT of Task 1 was actually 67-ms slower when it repeated from Task 2 of the previous trial than when it switched (see Figure 3).

In addition to the shortened RSI (Experiments 2 and 3) and semi-circular frame (Experiment 3), the display position of an ensemble (AB or BA) was fixed in Experiment 4. The results showed that the element-level switch cost of 182 ms obtained in Experiment 1 reversed to a switch benefit of 67 ms. A comparison between the element-level switch benefit of 67 ms in Experiment 4 with the element-level switch cost of 182 ms in Experiment 1 showed a significant two-way interaction of experiment and task order condition on RT, $F(1, 30) = 34.71$, $p < .01$, $MSE = 14{,}323$. Thus, this experiment provides further evidence that temporal and spatial contiguity between Task 1 and Task 2 reduce the switch cost on Task 1. A comparison between the results of Experiment 4 and Experiment 3 also revealed a significant interaction between experiment and task order condition on RT, $F(1, 30) = 7.89$, $p < .01$, $MSE = 14{,}070$. Therefore, the attempt to enhance recognition that an ensemble was repeated appears to have further increased the effect of task ensembles on the element-level switch cost.

Experiment 5

In Experiments 1 and 2, the four quadrants of the circular object were on the screen throughout the whole block to help participants keep track of the task sequence. In Experiments 3 and 4, however, only the two quadrants for the current Task 1 and Task 2 appeared on each trial. After participants responded to Task 2 of one trial, these quadrants disappeared and the 2 quadrants for the next Task 1 and Task 2 appeared. One might therefore argue that participants interpreted the color of the quadrants for next Task 1 and Task 2. This cue interpretation may represent a task of its own. Consequently, participants would have performed a task switch even when Task 1 was the same as Task 2 of the previous trial. We refer to this possibility as the cue-interpretation hypothesis. It is important to note that the task sequence was given in advance and repeated throughout the entire block (plus the immediately preceding practice block) in all experiments. Therefore, it seems unlikely that participants had to fully depend on the color cue. Nevertheless, Experiment 5 was designed to address this possibility.

Experiment 5 addresses another confound that might have caused a switch benefit in Experiment 4. In that experiment, each task in the fixed-order condition was always presented in the same location, whereas each task in the alternating-order condition was presented in one of two different locations. For example, the tasks in the sequence AB-AB were always displayed in the top and right quadrants, but the tasks in the sequence AB-BA were presented in the top and right quadrants then the bottom and left quadrants. Thus, Task A and Task B appeared in only one location in the former case but in two different locations in the latter case. It is conceivable that the consistent display location of Tasks A and B in the fixed-order condition led to a reduction in RT and hence can account for some of the switch benefit observed in that condition.

To address the cue-interpretation hypothesis and the potential confound between the task-order condition and number of display locations in Experiment 4, the critical change in Experiment 5 was that the same semi-circular frame was displayed on the screen throughout the entire experiment. As shown in Figure 2, this frame contained a black quadrant (Task A) on the left and a blue quadrant (Task B) on the right. Because the frame never changed, it is even more unlikely that cue interpretation was necessary. Another consequence of this design is that the location for a particular task was always the same, both in the fixed-order condition and the alternating-order condition. Thus, this experiment deconfounds task-order condition with the number of display locations per task.

Because the two quadrants of the semi-circular frame were fixed, the movement of stimuli between these two quadrants depended upon the task sequence. For example, in the fixed-order sequence AB-AB, the first stimulus appeared in the left quadrant and the second stimulus appeared in the right quadrant and so on. On the other hand, in the alternating-order sequence AB-BA, the first stimulus appeared in the left quadrant and the second stimulus appeared in the right quadrant; the direction was reversed for the third and fourth stimuli (i.e., from right to left quadrant). Note that the location of Task 1 was always the same as the previous Task 2 in the alternating-order condition, which should highlight the fact that it was an element-level task repetition.

Method

Participants. There were 16 participants in this experiment. They were students from the same participant pool as in the previous experiments, but none had participated in those experiments. All participants were required to have normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure were the same as in Experiment 4, except as noted. Two quadrants (Left and Right) were adjacent to each other on the screen. Left and Right Quadrants were always colored black and blue, respectively, to indicate that Task A (the magnitude task) would always be on the left side and Task B (the category task) would always be on the right side. Immediately after the feedback for the previous trial, an uninformative fixation point was presented for 300 ms in the quadrant for the next Task 1 (similar to Rogers & Monsell's, 1995, Experiment 5). The stimulus for Task 1 appeared 900 ms later. Thus, the RSI leading up to Task 1 was still 1,500 ms. The purpose of the fixation point was to ensure that participants would know the location of the stimulus for the upcoming Task 1.

In the fixed-order condition, the presentation of the AB-AB sequence was Left, Right Quadrant, then Left, Right Quadrant, and so on. The presentation of the BA-BA sequence was reversed (Right, Left Quadrant, then Right, Left Quadrant). In the alternating-order condition, the presentation of the AB-BA sequence was Left, Right Quadrant, then Right, Left Quadrant, and so on. The presentation of the BA-AB sequence was similar to the AB-BA sequence except that the presentation direction was reversed (Right, Left Quadrant, then Left, Right Quadrant).

Results and Discussion

Mean RT and PE for the four tasks in each cycle are shown in Table 1. The data analyses were performed in the same way as in the previous experiments. Approximately 4% of the trials were omitted because of the RT cutoffs. The effect of task order condition on Task 1 approached significance for RT, $F(1, 15) = 3.68$, $p = .07$, $MSE = 10{,}471$. Mean RT for Task 1 was 904 ms in the alternating-order condition (e.g., AB-BA) but was 855 ms in the fixed-order condition (e.g., AB-AB). Similar to Experiment 4, mean RT for Task 1 was 49-ms slower when it repeated from Task 2 of the previous trial than when it switched. No significant effect was found in the PE data. A comparison between Experiment 1 and Experiment 5, including experiment as a between-subject variable, showed a significant two-way interaction of experiment and task order condition, $F(1, 30) = 31.27$, $p < .001$, $MSE = 13{,}699$. Thus, the data once again indicate that temporal and spatial contiguity of Task 1 and Task 2 led to a reduction in the switch cost.

In Experiment 5, the same two quadrants frame (see Figure 2) was presented on the screen all the times. If the lack of a significant element-level switch cost was due to a cue-interpretation task in Experiments 3 and 4 or due to multiple locations used for the same task in the alternating-order condition in Experiment 4, then a significant element-level switch cost should have been found in Experiment 5. Yet, no element-level switch cost was found. In fact, similar to Experiment 4, Experiment 5 showed that responses to Task 1 were 49-ms faster when the element-level tasks switched than when they repeated. A comparison of the element-level switch benefit in Experiment 5 (49 ms) to that in Experiment 4 (67 ms) showed no significant difference between experiments, $F(1, 30) < 1.0$. This result suggests that the lack of the element-level switch cost in Experiment 4 was not due to interruption from a cue-interpretation task or the confound between the task order conditions and the display locations.

Experiment 6

The previous five experiments showed that even though the RSI leading up to Task 1 was unchanged across experiments, the element-level switch cost on Task 1 decreased and even reversed when variables likely to influence the formation of an ensemble of Task 1 and Task 2 were manipulated (see Figure 3 for switch costs obtained in Experiments 1 to 5). These results indicate that the element-level effect might have been eliminated. Alternatively, the element-level effect might still be present, but counteracted by an even larger ensemble-level effect that worked in the opposite direction. Because the design in Experiments 2 to 5 confounded the element-level and the ensemble-level variables (when the element-level task switched, the ensemble-level repeated, and vice versa), those data are not able to distinguish between these two interpretations.

Experiment 6 was designed to test these two possible interpretations by eliminating the confounding of the element-level and the ensemble-level variables. We measured the contribution of the element-level switch effect, while holding the ensemble-level effect constant. Specifically, the ensemble always repeated (i.e., we used the fixed-order condition only), but the element-level task could be a repetition or a switch. To achieve this goal, we presented three tasks on each trial (called Task 1, Task 2, and Task 3) that were temporally and spatially contiguous. This three-task sequence repeated throughout the whole block. Consider the task sequence of AAB-AAB-AAB, etc., versus the task sequence of ABA-ABA-ABA, etc. In both task sequences, the three-task sequence always repeats. However, Task 1 was always an element-level task switch from Task 3 of the previous ensemble in the former task sequence (AAB) but always an element-level task repetition in the latter task sequence (ABA). The experimental design, therefore, enables us to measure the element-level switch effect on Task 1, without being confounded with the ensemble-level switch effect.

To induce participants to form an ensemble of these three tasks, we adopted a similar approach to the one used in Experiment 5: The three tasks of each trial were presented within a single semicircular frame (containing three slices), separated by a short RSI (0-ms in this case). As in the previous five experiments, the RSI between trials (i.e., from Task 3 of one trial to Task 1 of the next trial) was 1,500 ms. If the element-level effect is eliminated by the formation of an ensemble of Tasks 1-3, then no switch cost on Task 1 should be observed in Experiment 6. However, if the element-level effect is still present, then a substantial switch cost, perhaps as large as that obtained in Experiment 1 (182 ms), should be observed. That is because the task ensemble always repeated regardless of whether Task 1 was an element-level switch or repeat; hence, the ensemble-level effect could not counteract the element-level effect.

Method

Participants. There are a total of 16 participants in this experiment. They were students from the same participant pool as in the previous experiments, but none had participated in those experiments. All participants were required to have normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure were the same as in Experiment 5, except as noted. A semi-circle object with three slices (left, middle, and right) was displayed in the center and remained on the screen throughout the whole block. The three tasks for each task sequences (Task 1, Task 2, and Task 3) were presented in order from left, middle, and right slices, separating by 0-ms RSI. Because the task presentation was constant throughout the whole experiment, the fixation point used in Experiment 5 seemed unnecessary, and therefore was removed. The feedback for the three tasks in each trial appeared immediately after the response to Task 3 was made and lasted for 300 ms. Task 1 for next trial appeared in the left slice of the semi-circle object 1,200 ms after the offset of the feedback message. Thus, the total RSI between trials was 1,500 ms, as in previous five experiments. The presentation of the task sequence was then repeated.

Two different element-level switch task sequences (AAB and BBA) and two different element-level repetition task sequences (ABA and BAB) were used. To minimize the number of times participants changed ensembles, half of the participants received only the task sequences of AAB and ABA, whereas the other half of the participants received only the task sequences of BBA and BAB. The order of the two tasks sequences was counterbalanced across participants. Participants first performed one practice block of 96 trials and four experimental blocks of 192 trials of one task sequence, followed by another practice block and four experimental blocks of the other task sequence. As in previous experiments, they were told that speed and accuracy were equally important.

Results and Discussion

Mean RT and PE for the three tasks in each task sequence are shown in Table 2. The data analyses were performed in a similar way as in the previous experiments. Approximately 3% of the trials were omitted in this data analysis because they fell outside RT cutoffs. The main purpose of Experiment 6 was to determine if the element-level switch cost on Task 1 is still evident, while holding the task ensemble effect constant. The switch cost was measured by comparing Task 1 in the switch condition (e.g., AAB) to Task 1 in the repetition condition (e.g., ABA) for each participant. Thus, the RT and the corresponding PE on Task 1 were analyzed as a function of Task 1 condition (switch versus repetition). The effect of Task 1 condition on RT was significant, $F(1, 15) = 14.83$, $p < .01$, $MSE = 4{,}764$. Mean RT for Task 1 was 832 ms in the repetition condition but was only 738 ms in the switch condition. In other words, participants responded to Task 1 approximately 94 ms faster when it was a task switch than when it was a task repetition. The main effect of Task 1 condition on PE was significant, $F(1, 15) = 7.20$, $p < .05$, $MSE = 0.0005$, with the error rate being .02 higher on Task 1 when it was a task switch than when it was a task repetition.

When the task ensemble always repeated, the performance on Task 1 of the current trial was 94 ms slower when it was a repetition from Task 3 of the previous trial than when it was a switch. The data therefore indicate that there is no switch cost between adjacent elements if they belong to different ensembles. The lack of the element-level switch cost in Experiment 6 suggests that the element-level effect is fragile and is diminished or eliminated when an ensemble of Tasks 1-3 is formed. Although there was no element-level effect between ensembles, it is important to note that Task 2 RT was in fact 331 ms slower when it was a switch from Task 1 than when it was a repetition (see Table 2). Thus, a substantial element-level task-switch effect was evident within an ensemble. The implication of this dissociation between the switch costs observed between and within ensembles will be considered in the General Discussion.

Although the main point of Experiment 6 is that there was no switch cost between ensembles (i.e., on Task 1 of an ensemble), it is worth noting that there was in fact a modest switch benefit of 94 ms. This finding raises the intriguing hypothesis that it is actually disadvantageous to repeat an element between ensembles. However, there is a more mundane explanation. In the task sequences AAB and BBA where Task 1 was an element-level switch, the control structure for the ensemble would contain only one switch (Task 2 to Task 3). However, in the task sequence ABA and BAB where Task 1 was an element-level repetition, the control structure for the ensemble would contain two switches (Task 1 to Task 2, and Task 2 to Task 3). Because the control structure is more complicated in the latter case than in the former case, it should result in slower RT for all three tasks of an ensemble. The present data are consistent with this interpretation. From Table 2, it can be seen that mean RT for Task 3 (always a task switch) was also about 94 ms slower when the control structure contained two switches in the task sequence ABA and BAB than when the control structure contained only one switch in the task sequence AAB and BBA. Thus, the simplest interpretation of these data is that there is no element-level effect on Task 1, but ensemble difficulty affects all three task elements by about 94 ms.

General Discussion

Research on task switching has led to an important finding, namely that task switching is associated with a substantial time cost. A residual switch cost has been observed even with a long RSI (e.g., Gopher et al., 2000; Goschke, 2000; Meiran, 1996; Roger & Monsell, 1995), predictable task-switch sequences (e.g., Tornay & Milán, 2001), task cueing (e.g., Hartley, Kieley, & Slabach, 1990), and practice (e.g., Meiran, 1996). Thus, even when task information and ample time are provided prior to a task switch, advance task preparation is still incomplete. Rogers and Monsell (1995) argued that the residual switch cost occurs because on-line task-set reconfiguration, triggered by the stimulus onset, is required to complete task preparation. Logan and Gordon (2001) proposed a quantitative model along the same lines, in which switch costs reflect the time required to transmit task-set parameters from working memory to the subordinate processor. There are differences between these and other task-switching theories, however as Gopher et al. (2000) summarized, "what all authors seem to agree on is that whatever factors are involved, their influence is not amenable to voluntary, advanced preparation" (p. 311).

The present study investigated a phenomenon, discovered but mostly neglected by De Jong (1995), in which the usually robust task switch cost disappears and even reverses. In De Jong's PRP paradigm, Task 1 and

Task 2 were presented in either a fixed order or alternating order throughout a block. Task 1 RT was (11 ms) faster in the fixed-order condition (e.g. AB-AB-AB, etc.) than in the alternating-order condition (AB-BA-AB, etc.). In other words, responses to Task 1 were faster when it was an element-level task switch than when it was an element-level task repetition from previous Task 2. Although the cause for this result is not entirely clear from De Jong's study, perhaps one important factor was the formation of an ensemble covering both Task 1 and Task 2 (see the Introduction for detailed discussion). The present study investigated this possibility and the implications for task-switching theories.

Can Switch Costs Be Eliminated or Reversed?

The purpose of Experiment 1 was to replicate the standard task-switching result and provide a baseline against which to compare the results of subsequent experiments. A constant 1,500-ms RSI was used between tasks. Thus, there was no reason for participants to form an ensemble of more than one task element – each task should be treated as an individual element. A substantial element-level switch cost of 182 ms was obtained, which replicated traditional task-switching studies using similar tasks.

In Experiments 2 to 5, the order of Task 1 and Task 2 was either fixed (e.g., AB-AB; the element-level switch condition) or alternating (e.g., AB-BA; the element-level repetition condition) within a block. To evaluate whether and how the preparatory state of an ensemble affects the switch cost, we manipulated task presentation variables likely to affect participants' perceptional organization of task elements (e.g., based on established principles of Gestalt Psychology), such as the temporal and spatial contiguity of Task 1 and Task 2. Experiment 2 increased the temporal contiguity by shortening the RSI between Task 1 and Task 2 to only 300 ms. In addition to this RSI reduction, Experiment 3 increased the spatial contiguity by presenting Task 1 and Task 2 within a common frame. Furthermore, Experiment 4 amplified the recognition that the ensemble of Task 1 and Task 2 had repeated (in the fixed-order condition) by presenting that ensemble in the same location on consecutive trials.

The element-level switch cost on Task 1 RT was reduced from 182 ms in Experiment 1 to 120 ms in Experiment 2, and to only 51 ms in Experiment 3. Even more surprisingly, the switch cost reversed to a significant 67-ms switch benefit in Experiment 4, meaning that responses to Task 1 were actually faster when it switched from the previous Task 2. In sum, we observed a powerful effect (from a cost of 182 ms to a benefit of 67 ms) of variables thought to influence ensemble formation. To the best of our knowledge, our study is the first to show an element-level switch benefit using dual-affordance tasks.

Experiment 5 was designed to test two alternative explanations for the switch benefit in Experiment 4. One purpose was to see if the absence of the element-level switch cost in Experiment 4 was due to the appearance of the two quadrants for the upcoming ensemble, which may have triggered an intervening cue-interpretation task. A second purpose was to examine if the lack of element-level repetition benefit in Experiment 4 was due to the use of two different display locations for each task in the alternating-order condition (e.g., AB-BA), but only one location for each task in the fixed-order condition (e.g., AB-AB). To address these issues, the same two colored quadrants were displayed on the screen throughout each block in Experiment 5 (just as in Experiment 1). Similar to Experiment 4, a 49-ms element-level switch benefit was obtained. Hence, significant reversal of the switch cost in Experiment 4 was not due to an intervening cue-interpretation task or to the number of locations used for each task.

The results from Experiment 1 to 5 showed that the element-level switch cost on Task 1 can be eliminated and even reversed when the ensemble of Task 1 and Task 2 is formed. This finding is difficult to explain within the framework of traditional task-switching theories. The important assertion of traditional task-switching theories is that advance preparation is inherently incomplete. As incorporated in Rogers and Monsell's (1995) on-line reconfiguration account, as well as Logan and Gordan's (2001) quantitative model, some aspects of reconfiguration cannot begin until the relevant stimulus appears. As long as the current task element is a switch from the previous task element, the stimulus-triggered reconfiguration should produce a cost. Consequently, the obvious expectation could be an element-level switch cost on Task 1 across the first five experiments. Surprisingly, the switch cost was reduced, and even reversed to show a switch benefit in Experiments 4 and 5. Hence, it appears that the stimulus-triggered reconfiguration is not the whole story for the switch cost.

Converging Evidence for Ensemble Formation

The pattern of switch costs across Experiments 1 to 5 showed a strong and clear trend: The more steps that were taken to encourage the formation of ensembles, the smaller the switch cost became (see Figure 3). It is natural therefore to conclude that task ensembles were formed and that ensemble formation caused the observed change in the switch costs. Furthermore, it would appear that the temporal contiguity manipulation by itself (Experiment 2) was much less effective than the combination of temporal and spatial contiguity (Experiments 3 to 5). Perhaps the spatial contiguity provided a strong cue as to which elements should comprise the ensemble, whereas temporal contiguity (300- versus 1,500-ms RSI) did not.

Although the switch costs observed in Experiments 1 to 5 are consistent with the claim that an ensemble of Task 1 and Task 2 was formed, it is worthwhile to ask whether there is any converging evidence across experiments for this claim. In Experiments 2-5, there was little time following the performance of Task 1 for participants to prepare for Task 2. If only Task 1 were prepared in advance of the trial, then Task 1 would be performed quickly but Task 2 would presumably be performed slowly (i.e., would show a large switch cost). However, by preparing for Task 1 *and* the subsequent switch to Task 2 prior to each trial, as suggested by De Jong (1995), the processing of Task 2 could be completed soon after the response for Task 1 has been executed (i.e., with relatively little switch cost). On might therefore expect that Task 1 RT should increase somewhat when people form an ensemble of Task 1 and Task 2, because instead of preparing for just Task 1 they now prepare for both tasks (e.g. to perform Task 1 and switch to Task 2). A comparison across experiments shows that Task 1 RT was in fact significantly slower in Experiments 2 to 5 than in Experiment 1 (see Figure 4), Fs(1, 30) $\geq$ 11.05, ps < .001, MSEs $\leq$ 20,321. For similar reasons, one might also expect Task 1 RT to increase from Experiment 2 to Experiment 5, based on the hypothesis that the probability of ensemble formation increased across these experiments. This pattern was not observed. The reason might be that participants in Experiment 1 did not successfully keep track of whether the task elements had a short or long RSI. As suggested by Rogers and Monsell (1995), when participants do not know they will have sufficient time to prepare for the upcoming task element, they might not engage in any preparation at all. Thus, Task 1 RT in Experiment 2 might have been elevated due to poor preparation.

In addition, one might expect to see Task 2 RT decreasing as the probability of ensemble formation increased from Experiments 2 to Experiments 4 and 5. Task 2 RT was significantly faster in Experiments 3 and 4 than in Experiment 2, Fs(1, 30) $\geq$ 4.26, ps < .05, MSEs $\leq$ 6,686. Although the comparison between Experiment 5 and Experiment 2 on Task 2 RT was not significant, F(1, 30) = 2.77, p = .1065, MSE = 7,218, the mean Task 2 RT was 87 ms faster in Experiment 5 than in Experiment 2. Thus, as apparent in Figure 4, overall response times for Task 2 did in fact decrease markedly from Experiments 2 to 5. This decrease in RT2 appears to closely track the decrease in the switch cost.

Another prediction is that when ensembles are formed Task 2 RT should be faster in the fixed-order condition, where the task ensemble always repeats, than in the alternating-order condition, where the task ensemble always switches. That is because the control structure for an ensemble (e.g., prepare Task 1 and the subsequent switch to Task 2) stayed the same for the task ensemble repetition, but changed for the task ensemble switch. Consequently, the advantage for repeating an ensemble should appear not only on Task 1 but also on Task 2. In contrast, if task elements are prepared individually, then performance on Task 2 in the fixed-order and alternating-order conditions should be equivalent. These predictions are essentially the same as the ones De Jong (1995; Experiment 3) described for Task 2 of his PRP paradigm. From Figure 4, it can be seen that Task 2 was in fact much faster in the fixed-order condition than in the alternating-order condition in Experiments 3 to 5. These data not only confirm De Jong's findings, but also provide converging evidence that our manipulation of ensemble formation was effective.

Another interesting finding that supports the ensemble formation hypothesis is that although the RSI leading up to Task 2 was only 300 ms in Experiments 2 to 5, mean Task 2 RT in the fixed-order condition was comparable to that in Experiment 1 (where the RSI was 1,500 ms). The equivalent Task 2 performance in these experiments suggests that ensemble preparation (prepare Task 1 and switch to Task 2) can completely compensate for the drastically shortened RSI.

Additive Effect Hypothesis

Although Experiments 2-5 indicate that performance depends strongly on the control structure of a multi-task ensemble, they do not necessarily indicate that there is no effect of switching cognitive operations from one task element to the next. Because the same stimulus set and the same motor responses were used for both tasks in all experiments, a change of the S-R mapping rules is required when the task element switches from the previous one, but not when it repeats. Therefore, it is highly plausible that there is some effect of switching between task elements even when an ensemble of Task 1 and Task 2 is formed. The main question, then, is how can we reconcile the present findings of the element-level switch benefit in Experiments 4 and 5 with traditional task-switching theories? A relatively minor modification to traditional task-switching theories is to assume that the switch cost reflects the net contributions from both element-level effect and ensemble-level effect. The key assumption of this additive effect hypothesis is that a roughly constant cost is obtained when the cognitive operations changed from one task element to the next. However, this cost is negated by an ensemble-level effect working in the opposite direction.

This model can explain the data from Experiments 1-5, as follows. In Experiment 1, a constant RSI was used within and between trials. The preparatory state concerns only one task, so there is no ensemble-level effect. The critical manipulation in the subsequent experiments involved forming an ensemble of Task 1 and Task 2. When an ensemble of Task 1 and Task 2 is formed, the ensemble-level effect works in the opposite direction as the element-level effect. This is because the alternating-order condition involves an element repetition but an ensemble switch, whereas the fixed-order condition involves an element switch but an ensemble repetition. The net result depends on the frequency with which an ensemble of Task 1 and Task 2 is formed and the relative strength of the ensemble- and element-level effects. To explain the element-level switch benefit in Experiments 4 and 5, it must be the case that the strength of the ensemble-level effect is greater than that of the element-level effect. To explain the fact that Experiments 2 and 3 reduced the element-level switch cost relative to Experiment 1, yet did not produce a benefit as in Experiments 4 and 5, one can assume that an ensemble containing Task 1 and Task 2 was formed on some trials but not all. Alternatively, one can also argue that the ensemble of Task 1 and Task 2 was formed in all trials in Experiments 2 and 3, but the strength of the ensemble-level effect was weaker than that of the element-level effect.

In order to test more stringently the additive effect hypothesis, it is necessary to distinguish between the individual contribution of the element-level effect and the ensemble-level effect. Yet, it is impossible to differentiate the effects of these variables in Experiments 1 to 5 because they were confounded (i.e., when the element-level task switched, the ensemble-level task repeated, and vise versa). Unlike the previous five experiments, which sometimes involved switching at the ensemble level (i.e., the alternating-order condition), Experiment 6 always repeated the three task elements for each trial (presumed to form an ensemble). However, Task 1 could still be an element-level repetition (e.g., ABA) or an element-level switch (e.g., AAB). This experiment revealed a 97-ms element-level switch benefit on Task 1. The absence of the element-level switch cost clearly contradicts any additive effect hypothesis in which it is assumed that there is substantial element-level effect. More generally, it appears that changing cognitive operations from one task element to the next does not always result in a substantial switch cost.

The Ensemble-Level Effect Only Hypothesis

The absence of the element-level effect in Experiment 6 raises the question of whether there is ever an element-level effect, caused by a change in cognitive operations. Perhaps there is no element-level effect but only an ensemble-level effect. The key assumption of this ensemble-level effect *only* theory is that switch costs are primarily due to the change in the control structure (which can concern one task element or multiple task elements, depending upon how the stimuli are presented). On this view, the slower performance on ensemble switch trials occurs because advance preparation for an ensemble switch is incomplete (similar to the way traditional task-switching theories explain the element-level effect).

This ensemble-level effect *only* hypothesis, by itself, can accommodate the major findings from Experiments 1 to 5 reasonably well. In Experiment 1, which used a constant RSI between tasks, participants should treat each task independently rather than group any two adjacent tasks as an ensemble. In other words, the control structure consisted of a single task. As a result, a switch cost should occur whenever the individual task changes, as observed in Experiment 1. In contrast, the task arrangement used in Experiments 4 and 5 strongly favored grouping Task 1 and Task 2 as an ensemble. Consistent with the ensemble-level effect *only* theory, a switch cost was obtained in the alternating-order condition (e.g., AB-BA) when the ensemble of Task 1 and Task 2 changed. Thus, this ensemble-level effect *only* theory not only can account for the element-level switch cost in Experiment 1 but also the reverse effect (switch benefit) in Experiments 4 and 5. To account for the intermediate results in Experiments 2 and 3, one need only assume that the manipulation of ensemble formation produced a mixture across trials of a control structure containing a single task and a control structure containing two tasks.

Although the ensemble-level effect only theory can account for the results of Experiments 1 to 5, it cannot easily account for the results of Experiment 6. In that experiment, Task 2 was 331-ms faster when it was an element-level repetition (e.g. AAB or ABA) than when it was an element-level switch (e.g. ABA or BAB). Thus, even though the switch cost was not observed between ensembles, it was observed within an ensemble. Since the ensemble always repeated, this switch cost cannot easily be explained in terms of an ensemble-level effect.

What Happened to The Element-Level Effect?

Taken together, our data seem to suggest that the element-level effect does occur in some situations but is fragile and does not occur in other situations. There are two obvious ways that the element-level effect could be reduced or eliminated: The repetition condition could lose its benefit or the switch condition could lose its cost. In other words, when the control structure concerns an ensemble of multiple task elements, element-level repetitions could become slower or element-level switches could become faster. From Figure 4, Task 1 RT in the fixed-order condition in Experiments 2-5 was generally comparable to that in Experiment 1. In other words, a similar Task 1 performance was observed for element-level switches, regardless of whether a task ensemble was formed. In contrast, Task 1 RT in the alternating-order condition increased dramatically from Experiments 1 to 5 as the likelihood of ensemble formation increased. In other words, the element-level repetition benefit on Task 1 observed in Experiment 1 disappeared when a task ensemble was formed. Based on this finding, it appears that the advantage of repeating the cognitive operation from one task element to the next is fragile and can be reduced or even eliminated depending on the control structure of the task elements to be performed.

A Dual-Route Model of Task Switching

The present data suggest that the method of task presentation affects how higher-level control structures are formed. When a control structure for an ensemble is formed, it might involve the preparation to perform one task element and the switch to the subsequent task element(s) within the ensemble. Within an ensemble (e.g., Task 1 to Task 2), a change in cognitive operations results in a large element-level switch cost. Between ensembles, on the other hand, a change in cognitive operations does not always result in a switch cost. Examination of the data across Experiments 1-5 reveals that the absence of the switch cost between ensembles is primarily due to the loss of the benefit in repeating task elements.

To account for the element-level and ensemble-level effects obtained in the present study, it is necessary to assume that the switch cost observed between two task elements is sensitive to the nature of task presentations. We propose that the benefit of repeating the task from one element to the next is fragile and occurs only under ideal circumstances. Specifically, it occurs only when no effort is made to establish a new preparatory state or re-establish the previous one. Perhaps advance preparation for an ensemble is sufficiently strong to wipe out the activations that are responsible for the task element repetition benefit. Within an ensemble, however, there is no active preparation so the advantage of repeating cognitive operations still arises.

These basic ideas are embodied in the following dual-route model of task switching. The key assumption of this model is that there are two different processing routes involved in task performance: conditional and unconditional. The conditional processing route is deliberate and relatively slow. It is amenable to advance preparation and therefore can benefit, up to a point, from a long RSI combined with a predictable task sequence. On the other hand, the unconditional processing route is relatively effortless and fast. It relies on the automatic carry-over of the mental state produced by performing the previous task element, which can be reapplied to the current task element (provided that the task repeats). This unconditional processing route is not amenable to advance preparation; in fact, advance preparation can overwrite the mental state carried over from the previous task element and force the use of the conditional route. Consequently, this route will not benefit from a longer RSI.

How does this dual-route model explain the residual switch cost found in the traditional task-switching studies (e.g., Meiran, 1996; Rogers & Monsell, 1995) and our Experiment 1? In these experiments, a predictable task sequence and a long, constant RSI were used. Task elements were presumably performed individually. Task switches must rely on the slow, conditional route. In contrast, task repetitions can rely on the fast, unconditional route because the mental state produced by performing the previous task element can simply be re-implemented without active preparation. Consequently, a substantial switch cost should occur, as has been observed.

Consider now a situation in which an ensemble of Task 1 and Task 2 is formed. The conditional route must still be used when task element switches, both within an ensemble and between ensembles. The unconditional route can still be used for task repetitions when they occur within an ensemble. However, this route cannot be used for task repetitions between ensembles (i.e., from the previous Task 2 to the next Task 1), because the ensemble preparation overwrites the mental state that carried over from the previous Task 2. Therefore, the conditional route will be used regardless of whether the task element repeats or switches between ensembles. The relative speed of these two conditions will therefore depend primarily on the degree of advance preparation for Task 1 in each condition. Task 1 performance should be faster in the fixed-order condition because the advance preparation always repeated, even though Task 1 was an element-level switch. Thus, this dual-route model can explain the switch benefit on Task 1 observed in our Experiments 4 and 5. In Experiment 6, because the ensemble always repeated, the degree of advance preparation for an ensemble should be roughly equivalent in the Task 1 element repetition condition (e.g., ABA) and the Task 1 element switch condition (e.g., AAB). Thus, there should be no switch costs between ensembles, as observed. Within an ensemble, however, no advance preparation occurred. Thus, task element repetitions could use the unconditional route, producing a large repetition benefit within an ensemble.

Note that even when both task repetitions and task switches are processed within the same conditional route, a repetition benefit can still be obtained under some circumstances. That is because the conditional route is sensitive to the degree of advance preparation and the preparation for task switches may be less than that for task repetitions. For instance, when the task sequence is not known in advance (unpredictable task sequence), the conditional route will be unprepared for a task switch but might still be properly configured for a task that repeats from the previous task element. Consequently, task repetitions will be performed faster than task switches. Thus, the dual-route model can account for the switch cost found in several studies with the unpredictable task sequence (e.g., Sohn & Carlson, 2000). In addition, because the configuration employed for the previous task element will become less available over time, these task repetitions might be performed more slowly as the RSI increases, as has been found (e.g., Sohn & Anderson, 2001). According to this dual-route model, one might also expect similar performance for unexpected task repetitions and expected task switches because both use the conditional route with a high degree of preparation (as found in Ruthruff, et al., 2001; Sohn & Anderson, 2001; Sohn & Carlson, 2000). To conclude, this dual-route model of task switching is straightforward, yet, provides a satisfactory account for our findings as well as those of many previous task-switching studies.

Related Findings

The present results suggest that performance of a series of tasks involves a high-level control structure that can cover multiple task elements (i.e., an ensemble) at the same time. One line of support for the notion of ensemble formation comes from studies showing hierarchical representation in sequence learning (e.g., Cohen, Ivry, & Keele, 1990; Keele, Cohen, & Ivry, 1990). In these sequence-learning studies, it is typical to present a single task with a series of responses that contains repeated patterns. Results suggest that the response sequence is likely to be coded as a series of chunks that are easy to carry out (e.g., Cohen, Ivry, & Keele, 1990). Our study also contained repeated patterns (e.g., AB-AB or AB-BA). Unlike the sequence learning studies, however, the pattern repeated at the task level not at the response level (the response pattern was completely random). In addition, the repeated task pattern was not the major factor leading to ensemble formation. Indeed, Experiment 1 contained the same task repeated patterns but there was no evidence of ensemble formation. Rather, the ensemble formation in our study was due to the temporal and/or spatial contiguity between the adjacent task elements.

Moreover, several previous studies have also shown that performance is better when a sequence of cognitive operations repeats than when it switches (e.g., Carlson & Lundy, 1992; Wenger & Carlson, 1995). For instance, Carlson and Lundy (1992) found that cascaded mathematical problem solving is more efficient when the sequences of operators are presented in a consistent order rather than in a varied order. Although this basic finding resembles that of the present paper, there are at least two major differences. One difference is that the mathematic problem-solving task in Carlson and Lundy's study involved a series of contingent (or cascaded) steps, where the result of one step served as an input to the next step. In our study, there was no contingency between the task elements. The stimulus and response for one task element were logically independent from those of the next task element. It is noteworthy that the sequence of cognitive operations has such a profound influence on performance even when they are not tightly bound by contingency and a common goal. More importantly, because the main focus in Carlson and Lundy's study was to understand the learning processes responsible for the effect of cognitive sequences, they did not directly address the crucial issue in the present study, which was the cost of switching between elementary cognitive operations.

Summary

The present study goes beyond previous task-switching studies by examining situations in which two non-overlapping tasks had the potential to form an ensemble. If task switching requires on-line reconfiguration as suggested by traditional task-switching theories, it would surely be surprising to observe a switch benefit. Yet, our study showed that the element-level switch cost diminished and even became a switch benefit when an ensemble of two tasks was likely to be formed. This result was primarily due to the loss of the advantage of repeating task elements. Although a switch benefit was observed across ensembles, a substantial switch cost between task elements was still obtained within an ensemble. To explain this pattern of results as well as previous findings, we proposed a model in which tasks are carried out using one of two routes, a fast unconditional route or a slow conditional route. This dual-route model, based on a solid empirical foundation, characterizes the complex interaction between higher-level control structures and the lower-level cognitive operations.

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Footnotes

1 Fagot (1994) referred to such tasks as "bivalent" tasks.

2 In task-switching studies, the term *task* sometimes refers to a rule used to map individual stimuli to individual responses and sometimes refers to an instance in which the rule is applied. For clarity, in the present study, we used *task* to refer to a type of stimulus-response mapping rule and used *task element* (or *element*) to refer to an instance of a task.

3 The term *switch benefit* merely indicates that responses were faster in the switch condition than the repetition condition. It is not necessarily meant to imply that there is an actual positive effect of element-level task switching.

4 Because a slightly different paradigm was used in Experiment 6, details of that experimental design will be described later.

5 For all experiments reported in this paper, essentially the same pattern of results was obtained even when the data were analyzed without the RT cutoffs.

Authors Note

Mei-Ching Lien and Eric Ruthruff, National Aeronautics and Space Administration (NASA) Ames Research Center, Moffett Field, California.

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Correspondence concerning this article should be sent to Mei-Ching Lien at Mail Stop 262-4, NASA Ames Research Center, Moffett Field, CA 94035. Electronic mail may be sent to mclien@mail.arc.nasa.gov.

Table 1.

Mean Response Times in ms (Proportion of Errors in Parenthesis) for Task 1 and Task 2 of Each Cycle in the Fixed-Order Condition (ABAB and BABA Sequences) and the Alternating-Order Condition (ABBA and BAAB Sequences) in Experiments 1-5. (A: Magnitude Task; B: Category Task).

Condition	Sequence	Task 1	Task 2	Task 1	Task 2
		Experiment 1			
Fixed-Order	ABAB	758 (.03)	818 (.04)	773 (.04)	814 (.05)
	BABA	857 (.07)	801 (.05)	842 (.05)	773 (.05)
Alternating-Order	ABBA	614 (.04)	806 (.05)	613 (.03)	747 (.02)
	BAAB	662 (.03)	745 (.04)	611 (.03)	806 (.03)
		Experiment 2			
Fixed-Order	AB-AB	990 (.05)	956 (.05)	922 (.03)	931 (.04)
	BA-BA	973 (.03)	965 (.06)	959 (.03)	929 (.03)
Alternating-Order	AB-BA	892 (.04)	944 (.01)	834 (.01)	945 (.06)
	BA-AB	822 (.02)	872 (.04)	816 (.02)	917 (.05)
		Experiment 3			
Fixed-Order	AB-AB	923 (.03)	817 (.03)	866 (.03)	821 (.03)
	BA-BA	929 (.03)	783 (.03)	914 (.04)	807 (.04)
Alternating-Order	AB-BA	880 (.06)	862 (.05)	855 (.04)	823 (.05)
	BA-AB	903 (.05)	821 (.04)	791 (.03)	876 (.03)
		Experiment 4			
Fixed-Order	AB-AB	873 (.03)	814 (.05)	848 (.04)	767 (.04)
	BA-BA	873 (.03)	759 (.05)	865 (.03)	748 (.05)
Alternating-Order	AB-BA	939 (.04)	864 (.02)	921 (.04)	777 (.04)
	BA-AB	927 (.03)	831 (.03)	939 (.03)	840 (.02)
		Experiment 5			
Fixed-Order	AB-AB	801 (.03)	755 (.03)	807 (.03)	800 (.04)
	BA-BA	893 (.03)	830 (.03)	918 (.05)	807 (.04)
Alternating-Order	AB-BA	884 (.03)	860 (.03)	907 (.03)	879 (.03)
	BA-AB	894 (.04)	949 (.03)	930 (.03)	880 (.02)

Note: The shaded cells refer to Task 1 and the non-shaded cells refer to Task 2. The element-level switch cost on Task 1 is measured by subtracting the alternating-order condition (element-level repetition) from the fixed-order condition (element-level switch).

Table 2.

Mean Response Times in ms (Proportion of Errors in Parenthesis) for Task 1, Task 2, and Task 3 in the Task 1 Repetition Condition (Task Sequences of ABA and BAB) and the Task 1 Switch Condition (Task Sequences of AAB and BBA) in Experiment 6. (A: Magnitude Task; B: Category Task).

Condition	Sequence	Task 1	Task 2	Task 3
Task 1 Repetition	ABA	821 (.02)	881 (.06)	762 (.05)
	BAB	843 (.02)	909 (.06)	927 (.04)
Task 1 Switch	AAB	715 (.04)	529 (.01)	730 (.05)
	BBA	761 (.05)	598 (.03)	769 (.09)
Switch Cost		- 94 (.03)	331 (.04)	

Note: The shaded cells refer to Task 1. The switch cost on Task 1 is measured by subtracting Task 1 repetition condition from Task 1 switch condition, whereas the switch cost on Task 2 is measured by subtracting Task 1 switch condition (Task 2 repeat) from Task 1 repetition condition (Task 2 switch).

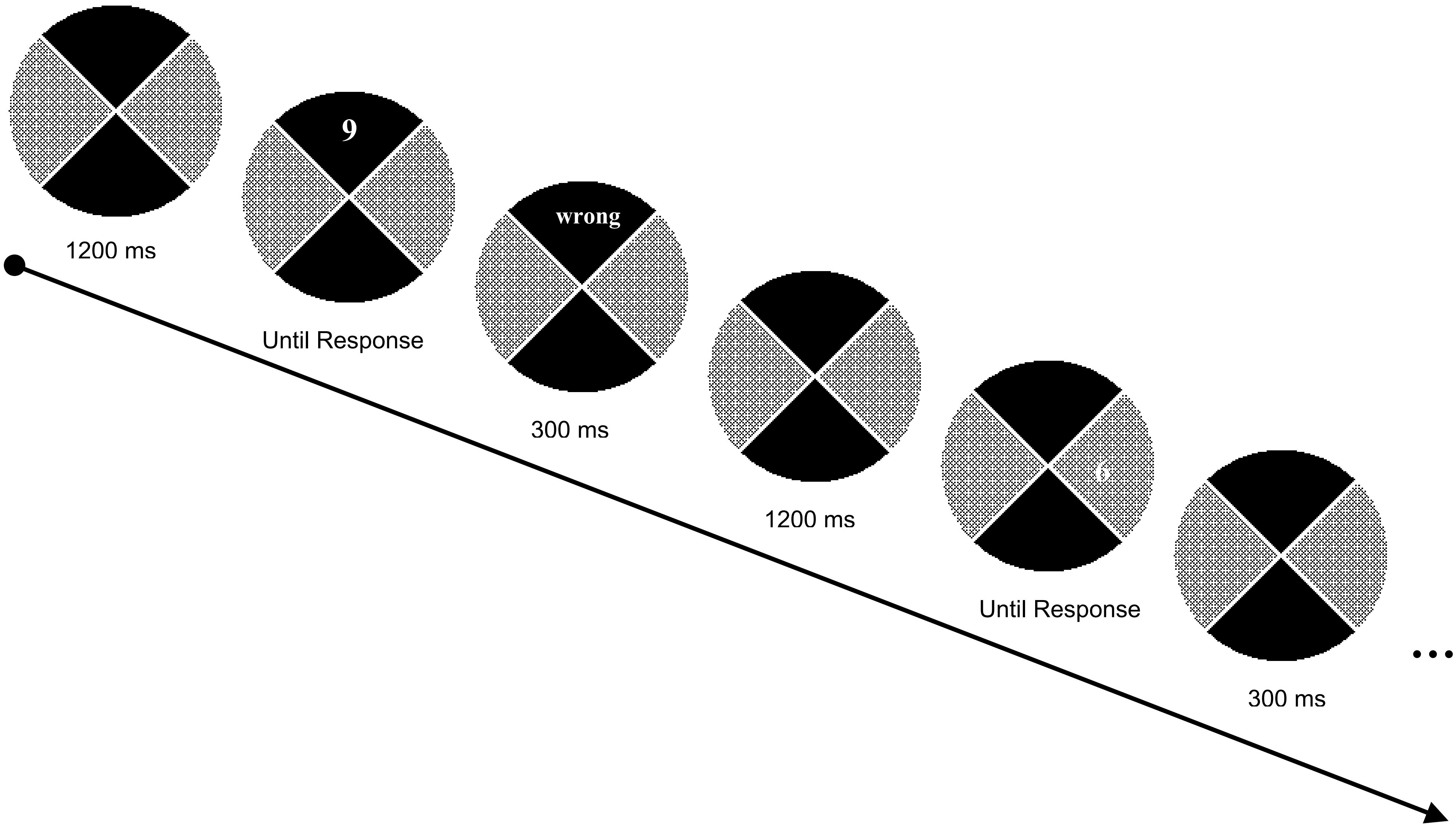
Figure Captions

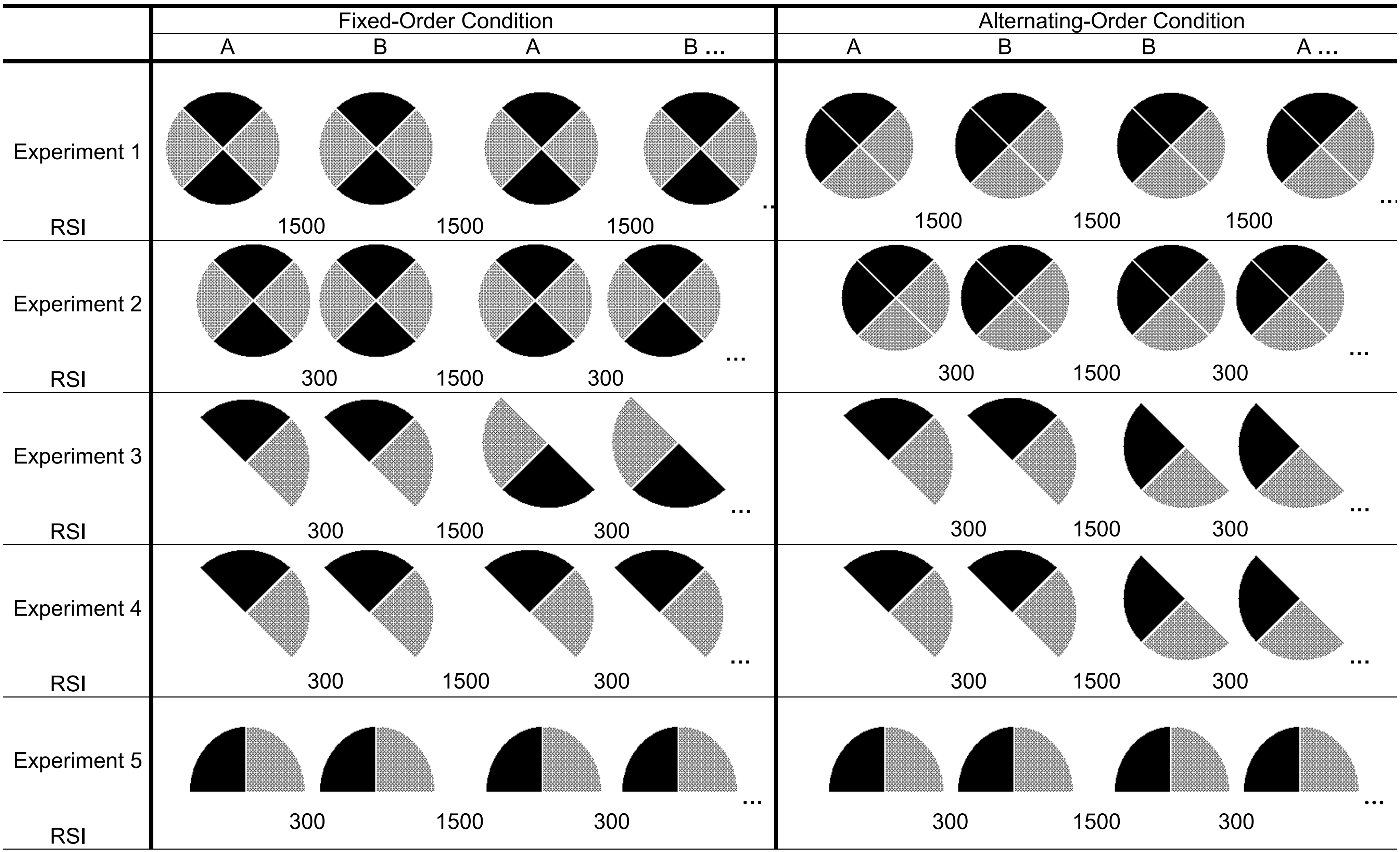
Figure 1. An example of the time course of task presentation used in Experiment 1. The black quadrant corresponds to the magnitude task (Task A) and the gray quadrant (which was blue in the actual experiment) corresponds to the category task (Task B).

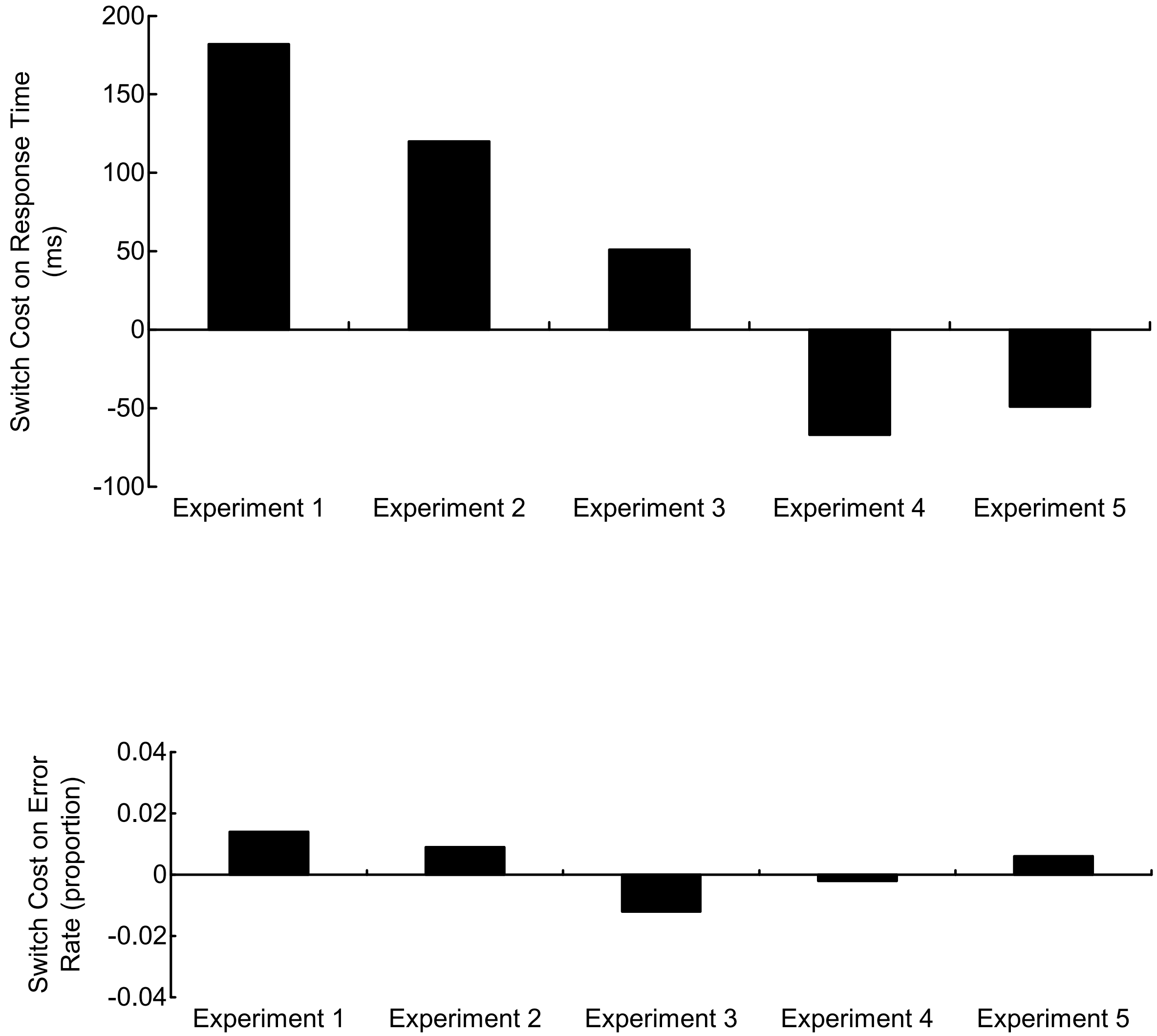
Figure 2. An example of the stimulus arrangement for the fixed-order condition (ABAB) and the alternating-order condition (ABBA) used in Experiments 1-5. (RSI: response-stimulus interval). The black quadrant corresponds to the magnitude task (Task A) and the gray quadrant (which was blue in the actual experiment) corresponds to the category task (Task B).

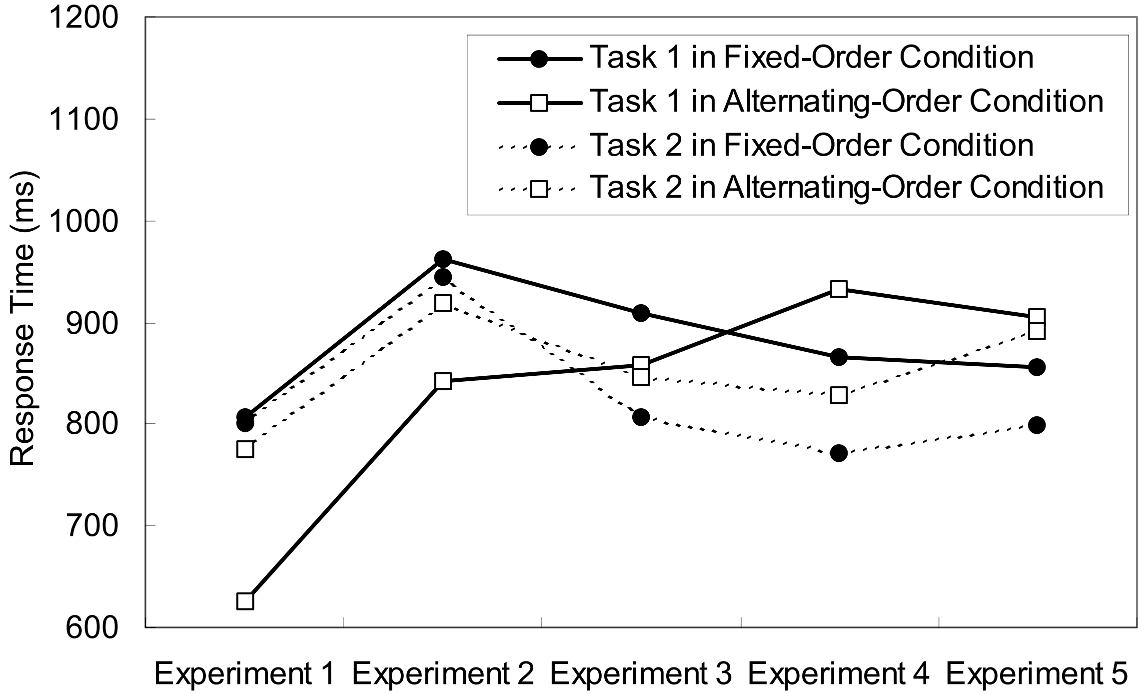
Figure 3. The element-level switch cost for mean response time (in ms) and proportion of errors on Task 1 in Experiments 1 to 5.

Figure 4. Response times for Task 1 and Task 2 (in ms) as a function of task order condition (the fixed-order condition and the alternating-order condition) in Experiments 1 to 5.


9
wrong
6
1200 ms
Until Response
300 ms
1200 ms
Until Response
300 ms
...


Fixed-Order Condition
A B A B ...
Alternating-Order Condition
A B B A ...
Experiment 1
RSI
1500 1500 1500
1500 1500 1500
Experiment 2
RSI
300 1500 300
300 1500 300
Experiment 3
RSI
300 1500 300
300 1500 300
Experiment 4
RSI
300 1500 300
300 1500 300
Experiment 5
RSI
300 1500 300
300 1500 300


Switch Cost on Response Time (ms)
200
150
100
50
0
-50
-100
Experiment 1
Experiment 2
Experiment 3
Experiment 4
Experiment 5
Switch Cost on Error Rate (proportion)
0.04
0.02
0
-0.02
-0.04
Experiment 1
Experiment 2
Experiment 3
Experiment 4
Experiment 5



1200
1100
1000
900
800
700
600
Response Time (ms)
Task 1 in Fixed-Order Condition
Task 1 in Alternating-Order Condition
Task 2 in Fixed-Order Condition
Task 2 in Alternating-Order Condition
Experiment 1
Experiment 2
Experiment 3
Experiment 4
Experiment 5