Task Switching in a Callosotomy Patient and in Normal Participants: Evidence for Response-Related Sources of Interference

Richard B. Ivry and Eliot Hazeltine

ABSTRACT We examined multitask coordination in neurologically healthy subjects and in a callosotomy patient. Subjects in two new experiments responded to two successive stimuli separated by a variable stimulus onset asynchrony (SOA), with the left hand to the first stimulus and with the right hand to the second. The task-relevant dimension for the two stimuli was the same for both hands or required a change in task set. For all subjects, reaction time to the second stimulus was inversely related to SOA, an effect referred to as the "psychological refractory period" (PRP). For control subjects, the effect of switching set was either additive or overadditive with SOA, whereas, for the callosotomy patient, no difference was observed between the same- and different-set conditions, even when the stimuli were presented along the vertical meridian and presumably available to both hemispheres. These results indicate that the primary locus of interference associated with task switching arises at processing stages associated with response preparation, selection, or initiation. Unlike the control subjects, the split-brain patient was able to maintain separate stimulus-response mappings in the two hemispheres.

17.1 COORDINATION OF BEHAVIOR AFTER CALLOSOTOMY

Callosotomy (split-brain) patients provide a unique opportunity for exploring the organization of our cognitive architecture (Sperry 1982; Gazzaniga 1995). Most of the split-brain work has addressed issues related to hemispheric specialization, focusing on identifying the basic capabilities of the two cerebral hemispheres in the areas of perception, memory, and language, although researchers have also studied these patients to learn how information processing is integrated and coordinated between the hemispheres. In general, perceptual studies have demonstrated that, while each hemisphere in isolation is capable of deriving perceptually and semantically rich representations, the integration of this information is dependent on callosal fibers (see Corballis 1995). Attention studies have provided even more impressive evidence of the general competence of each hemisphere (Luck et al. 1994). For example, Holzman and Gazzaniga (1985) found that split-brain patients were able to monitor two lateralized stimulus sequences without interference, whereas control subjects showed extensive cross talk between the two sequences, suggesting an inability to segregate the two sources of information.

Results such as these might suggest that the callosotomy operation functionally splits an individual into two separate halves. And yet the
very success of this operation argues against such an extreme conclusion. Indeed, from simple observation, it is impossible to discern any indication that the hemispheres are operating in isolation of one another (Bogen 1993). The actions of split-brain patients are quite coherent: they move about, talk, and use tools like neurologically intact individuals.

While the actions of split-brain patients continue to manifest at least some integration (Sergent 1987), this does not mean that the selected actions following callosotomy are the result of integrated processing between the two hemispheres (see Kingstone and Gazzaniga 1993). Rather, each hemisphere may independently control the actions of the contralesional limbs. For example, in a bimanual drawing task, split-brain patients performed the same when the component movements entailed orthogonal spatial trajectories as when the movements entailed parallel trajectories (Franz et al. 1996), whereas normal subjects showed severe interference (see also Franz et al. 1991). It appears that for tasks such as these, the subjects must generate two spatial plans, one associated with movement of the right hand and a second with movement of the left. In normal subjects, cross talk between these two representations produces interference when the representations entail conflicting spatial trajectories and goals. Rather than reflecting the operation of an integrated control operation, this interference presumably involves communication across the corpus callosum.

These results suggest that separate response plans can be generated and selected in the isolated cerebral hemispheres, although further examination of the patients' performance on these drawing tasks indicates that the initiation of these responses continues to be severely constrained (Franz et al. 1996). In contrast to their spatial uncoupling, the movements of the right and left hands remain tightly coupled in the temporal domain (see also Tuller and Kito 1989). Thus, there is a striking dissociation between the two well-documented constraints on bimanual movements. The callosotomy operation leads to spatial uncoupling, yet has minimal effect on temporal coupling.

17.2 DUAL-TASK PERFORMANCE AFTER CALLOSOTOMY

We have recently examined the dissociation of spatial and temporal constraints in a very different context (Ivry et al. 1998). In our dual-task study, subjects made two successive speeded responses to two different stimuli, the psychological refractory period (PRP) paradigm, in which one stimulus always appears first and subjects are instructed to respond as quickly as possible to this event (RT1). The second stimulus appears after a variable stimulus onset asynchrony (SOA), and also requires a speeded response (RT2). Across a wide range of studies, the time required to respond to the second stimulus is longer when the SOA between S1 and S2 is short than when it is long (see reviews by Pashler 1994; chap. 12, this volume; Meyer and Kieras 1997). The inverse relationship between RT2 and SOA has been dubbed the "psychological refractory period" or "PRP effect."

The analysis of the PRP effect has been useful for examining the architecture of human cognition, seeking to determine the limitations in multi-task coordination (see Pashler, chap. 12, Jolicoeur, Dell'Acqua, and Crebo, chap. 13, and Kieras et al., chap. 30, this volume). In Pashler's influential model, perceptual analysis and response execution are assumed to be independent processing stages for the two tasks. The critical limitation in dual-task performance, according to Pashler, is associated with response selection, which cannot occur in parallel for the two tasks. Rather, it is assumed that there is a unitary response selection process that must be accessed successively, first for task 1 and then for task 2. With short SOAs, response selection for task 2 must be delayed until this process is completed for task 1.

Pashler et al. (1994) tested three split-brain patients on a PRP task. The design involved the lateralized presentation of two up-down spatial discrimination tasks, with the onset of the tasks separated by a variable SOA. The first stimulus was presented to the left visual field (right hemisphere), and the subjects indicated the position of the stimulus by pressing one of two keys with the left hand. The second stimulus was presented to the right visual field (left hemisphere) and, correspondingly, was responded to with the right hand. The results convincingly demonstrated a robust PRP effect for all of the callosotomy patients.

Given our evidence that split-brain patients could maintain separate spatial plans in the two hemispheres (Franz et al. 1996), we sought to examine the persistent PRP effect in greater detail (Ivry et al. 1998, exps. 2 and 3). We used the same spatial discrimination tasks as Pashler et al. However, in separate blocks, the consistency between the two S-R mappings was manipulated (e.g., the spatial S-R mapping for the two hands was either symmetric or reversed). Because similar manipulations have been shown to affect response selection processes (McCann and Johnston 1992), we expected that the consistency manipulation would produce additive effects with SOA for RT2 (see also Duncan 1979).

As predicted, the consistency manipulation had a substantial effect on the performance of the control subjects. A PRP effect, additive or overadditive with SOA, was found for both consistent and inconsistent S-R pairings. There was substantial slowing of RT1 in the inconsistent condition, even though subjects were instructed to give priority to this task. The results were strikingly different for patient JW. (Ivry et al. 1998). While the PRP effect was again present, the consistency manipulation was underadditive with SOA and there was no cost on RT1. That is, the split-brain patient responded as fast to stimulus 1 when the two S-R mappings were inconsistent with one another as when they were consistent.
These results provide further confirmation of spatial uncoupling after callosotomy. The split-brain patient showed no cost attributable to the maintenance of inconsistent spatial S-R mappings in the two hemispheres. Moreover, the patient showed underadditivity between the effects of the S-R mappings and SOA, suggesting that the effect of the consistency manipulation influenced processing in or before the bottleneck. Thus whatever processing limits may persist following callosotomy, they do not appear to be associated with the same limitation on response selection identified in PRP studies with control subjects.

On the other hand, the split-brain patient did show a persistent delay in RT2 at short versus long SOAs, indicating that the two hemispheres were not completely independent. The source of this interference remains unclear, although, given the pattern of underadditivity, it arises at a relatively late stage of processing. One possibility is that the bottleneck for the split-brain patient is associated with a subcortical process associated with response implementation, a process accessed by action commands from the two hemispheres. There is evidence that such a limitation in response implementation also exists for normal participants, but is not typically evident because they bottleneck at an earlier stage of processing (De Jong 1993; Ruthruff, Johnston, and Van Selst forthcoming). Another hypothesis is that the persistent PRP effects reflect a strategy adopted by the split-brain patients to comply with the task instructions to make two successive responses (Meyer and Kieras 1997).

17.3 TASK SWITCHING AFTER CALLOSOTOMY

Many real-world situations require highly flexible behavior. For example, when approaching an exit on the highway, you may note the fuel gauge on your car and start looking for a gasoline station. As you turn off, however, the clamoring of the children, as well as the growls of your stomach may redirect your action toward the fast-food restaurant for a quick lunch. This fluctuation as to the goals of behavior is termed task switching (Allport, Styles, and Hsieh 1994; Rogers and Monsell 1995; Spector and Biederman 1976), reflecting the change in the salience of different stimulus properties as well as the viable responses.

In the typical task-switching experiment, subjects are required to switch between two tasks, each involving distinct S-R mappings. For example, for one task, subjects judge whether a digit is odd or even; for a second, they judge whether the digit is greater or less than 5 (Allport, Styles, and Hsieh 1994). Or they may be presented with bivalent stimuli and have to alternate between responding on the basis of the shape or color (Hayes et al. 1998). Switching costs are evident from the fact that reaction times are longer when the task set changes (e.g., color to shape) than when the task set remains constant (e.g., shape to shape). These costs are assumed to reflect the time required to retrieve and instantiate a new task set (see Pasler, chap. 12, Goschke, chap. 14, Meiran, chap. 16, and Kieras et al., chap. 30, this volume). Moreover, competition is also likely at the time of the switch between the old and new sets (Allport and Wylie, chap. 2, this volume; Mayr and Keele forthcoming).

We were interested in whether task-switching costs would be evident after callosotomy when the two tasks were associated with different hemispheres. Task-switching costs reflect limitations in our ability to maintain multiple goals and coordinate the processes required to achieve these goals. In Ivry et al. 1998, we had observed that, unlike control subjects, the split-brain patient J.W. could maintain separate, and even conflicting, stimulus-response mappings for his two hands. Thus, when two tasks were assigned to separate hemispheres, he did not show a limitation evident in normal individuals.

The generality of this claim may be limited, however. First, tasks that have shown independence between hemispheres after callosotomy have generally been spatial in nature (e.g., Franz et al. 1996; Luck et al. 1989; Holtzman and Gazzaniga 1985). It is unknown whether such independence would be observed with nonspatial tasks. Second, in Ivry et al. 1998, the task sets remained constant for each block of trials. Thus neither hemisphere was ever required to switch set. In the following studies, we examine what happens when the mappings need to be continually modified from trial to trial. Specifically, will a split-brain patient show signs of interference between the two hemispheres when the task requires continuous task switching?

Experiment 1

We employed a hybrid task that combined features of task switching and PRP experiments. On each trial, the subjects were required to make two successive responses. For the first task, a colored shape, a blue or green square or triangle, was presented in the left visual field; subjects made a speeded response with the left hand, identifying in separate blocks, either its shape or color. For the second task, one of four univalent stimuli was presented in the right visual field requiring a second speeded response with the right hand (see figure 17.1). This stimulus could be defined either by its color (a blue or green circle) or by its shape (a white square or triangle). A 4:2 mapping was used for the right hand, with one color and one shape assigned to each of two response keys. Stimulus onset asynchronies of 50, 150, 400, and 1,000 msec separated the presentation of the two stimuli. Task-switching costs were expected on trials in which the second stimulus was defined on a dimension different from that used to define the first stimulus. For example, if task 1 required the identification of shape, then task-switching costs would be evident by comparing response latencies when task 2 also required a shape judgment to those when task 2 required a color judgment.
two hands. For example, we could look at filtering costs by comparing response latencies for task 1 on trials where the irrelevant dimension was congruent with the relevant dimension, to those where the irrelevant dimension was incongruent with the relevant dimension.

Subjects Our split-brain patient was again J.W., who had participated in Ivry et al. 1998, a right-handed 44-year-old male who underwent a two-stage callosotomy operation in 1979 for the treatment of intractable epilepsy. MRI scans reveal that all of the fibers of the corpus callosum and posterior commissure were sectioned and that the anterior commissure is intact. J.W. continues to take antiepileptic medication, and seizure activity has been minimal postoperatively. His recovery has been excellent, and he has no difficulty in everyday activities (Gazzaniga 1998; Gazzaniga et al. 1984).

J.W. was administered the Wechsler Adult Intelligence Scale (WAIS-R) postoperatively, scoring 97 and 95 on the verbal and performance subtests, respectively. He has participated in neuropsychological studies for almost twenty years now (Gazzaniga 1995). He is able to comprehend language in both hemispheres; indeed, even when performing tasks where the input is restricted to the right hemisphere and responses are made with the fingers on the left hand, verbal instructions are sufficient. J.W. is adept in using his hands, as evidenced by his two favorite hobbies, drawing and building model cars, but does show mild clumsiness in finger movements with the left hand.

Three control subjects were tested; one male, aged 40, and two females, aged 48 and 42. All were right-handed and, based on self-report, had no known neurological disturbance. One of the authors (R.L.) served as a control and was aware of the hypotheses under study. The other two control subjects were naive as to the purposes of the experiment.

Procedure The experiment was conducted with a PC-based computer system. Two customized response boards were used, one for the left hand and one for the right hand, with participants using the index and middle finger of each hand to press low-resistance response keys measuring 10 x 1.9 cm. To maximize the participants’ comfort, the keyboards were oriented at 45 degrees with respect to the frontal plane.

A cross, 2 degrees on a side, was present at the center of the monitor at all times, and subjects were instructed to focus their eyes on this fixation marker. Each trial began with the 200 msec presentation of a bivalent stimulus in the left visual field. This stimulus was either a triangle or square, colored green or blue. The side of either object subtended a visual angle of 2.2 degrees and the center-to-center distance from the object to the fixation marker was approximately 9 degrees. On shape blocks, subjects were to respond with the left hand, pressing with the middle finger if the stimulus was a triangle, and with the index finger if
the stimulus was a square. On color blocks, the middle finger was to be used if the stimulus was green, and the index finger if the stimulus was blue. Subjects were told to ignore the value on the irrelevant dimension.

After an SOA of 50, 150, 400, or 1,000 msec, the stimulus for task 2 appeared for 200 msec, 9 degrees to the right of fixation. Unlike first-task stimuli, second-task stimuli were univalent, either a green or blue circle or a white square or triangle. Subjects were taught a 4:2 mapping and responded on one of two response keys with the right hand. To maintain a consistent mapping with task 1, the middle finger for the right hand was used to respond to the triangle and green circle, and the index finger was used to respond to the square and blue circle. A 3 sec window was provided during which the participant could complete the two responses before the next trial began. A 2 sec intertrial interval separated the response to the second-task stimulus on trial n from the onset of the first-task stimulus on trial n + 1, with the fixation marker present during this intertrial interval.

The subjects were repeatedly instructed to maintain fixation at the center of the screen. Although we did not monitor eye movements, J.W. has participated in many similar experiments and is quite good at maintaining fixation. While the subjects were encouraged to make fast and accurate responses for both tasks, they were explicitly told that their primary responsibility was to respond as quickly as possible to the first stimulus. They were informed that variable delays would occur between the two stimuli and that they should not wait for the second stimulus before making their first response. These instructions were repeated before each block of trials.

Subjects were tested in test blocks of 64 trials formed by the factorial combination of four color-shape combinations for stimulus 1, four univalent values for stimulus 2, and four SOAs. Four test blocks were completed in which the relevant dimension for task 1 was shape, and another four in which the relevant dimension for task 1 was color. Within each block, there were 32 trials on which the relevant dimension for task 2 was the same as for task 1 (nonswitch) and 32 trials on which the relevant dimension for task 2 was different (switch). Practice blocks, consisting of 16 trials were performed before the first test block for each of the first-task color and shape conditions. Visual feedback, presented at the center of the display, was provided after errors on either task during the practice blocks; this was repeated until the experimenter judged subjects to have learned the stimulus-response mappings and generally involved 2-3 repetitions. No on-line feedback was given during the test blocks, although the percent correct and mean reaction times for tasks 1 and 2 were displayed at the end of each block.

J.W. was tested on first-task color and shape conditions on separate days, with a four-day break between the sessions. Due to technical problems, the data were lost for the final two test blocks in the color condition. Thus, J.W.'s results are based on six blocks, two color and four shape. The control subjects each completed four test blocks of the color and shape conditions in a single session with a 15 min break separating the two conditions. Testing began with the first-task color condition for half of the controls and with the first-task shape condition for the other half.

Results and Discussion Our primary goal in this experiment was to determine whether the split-brain patient would show evidence of cross talk between the two tasks. In particular, would a task-switching cost be observed when the relevant dimension for task 2 differed from the relevant dimension for task 1. This question could be addressed in within-subject analyses because the design entailed both nonswitch and switch trials. Thus we used within-subject repeated-measure analyses of variance (ANOVA), with test block treated as the repeating measure.

A three-way ANOVA was used to measure task switching, with the variables task (color, shape), set (nonswitch, switch), and SOA (50, 150, 400, 1,000 msec). Only trials on which both response 1 and response 2 were correct were included. Figure 17.2 shows the mean response latencies for tasks 1 and 2 on these trials. Because there were no systematic differences in performance whether the first task required responses based on color or shape, the data in the figure are combined over the color and shape blocks. While there were some main effects and interactions involving the task variable for the control participants, these effects were inconsistent. Furthermore, given that task and order were confounded for each individual, it is unclear whether these effects are related to idiosyncratic differences in discriminability between the color and shape stimuli or to practice effects. Given this, we collapsed data over this variable to examine the other variables, verifying that all of the basic conclusions were essentially the same regardless of the relevant dimension for task 1.

A PRP effect is seen for all of the participants, with the main effect of SOA reliable at the 0.001 level in all of the analyses. The current findings of a robust PRP effect in a split-brain patient are in accord with previous studies (Pauley et al. 1994; Ivry et al. 1998) and indicate a persistent source of constraint in the timing or scheduling of the two responses. Most relevant for the present study, second-task response latencies are similar in the nonswitch and switch conditions for J.W. Although his latencies were slower on both tasks for the shortest SOA, neither the effect of set, nor the interaction of set and SOA were significant: F(1, 4) = 1.0 and F(3, 12) = 1.1, respectively. Thus J.W. does not appear to show a cost in changing response set when the two tasks are associated with different hemispheres.

A very different picture is evident for the control subjects. The effect of set was significant for all of the controls—R.L.: F(1, 6) = 51.0, p < 0.001; M.S.: F(1, 6) = 27.8, p < 0.005; A.L.: F(1, 6) = 187.6, p < 0.001. The interac-
nor any interactions between these variables. On the other hand, the control participants were less successful in keeping the two tasks segregated. RTI tended to decrease with SOA, with a main effect for SOA observed for M.S. and A.L.: $F(3, 18) = 3.4, p < 0.05$ and $F(3, 18) = 4.2, p < 0.05$, respectively. For R.L., this factor interacted with set, due to slower responses to the first stimulus when the second stimulus required a shift in set at the short SOAs: $F(3, 18) = 4.7, p < 0.05$.

In the preceding analyses, the same set trials are composed of two very different types of conditions. In one condition, the task-relevant stimulus value is identical for tasks 1 and 2, and correspondingly, the two responses entail homologous effectors. For example, in the color condition, the task-relevant stimulus might be green for both tasks, requiring successive keypresses with the middle finger of the left and right hands. In the other condition, even though the set remains the same, the task-relevant stimulus values differ and the responses are made with non-homologous effectors. For example, the task-relevant stimuli for tasks 1 and 2 might be blue and green, respectively, requiring successive responses with the index and middle fingers of the left and right hands. It is important to assess whether the results observed for the control subjects might reflect repetition benefits, either on the stimulus or response end, rather than task-switching costs. This is especially relevant given that the stimuli for task 2 were univalent.

We evaluated the effects of repetition benefits by performing additional analyses in which we focused on whether the two responses were made with homologous or nonhomologous fingers. For these analyses, we defined a new variable, “response relationship” (homologous, non-homologous), and examined the effects of this variable by itself and as a function of whether the set remained the same or switched. Because the number of observations per condition is relatively small, we combined the data over SOA. Note that when the set remains the same, responses with homologous effectors also entail a repetition of the task-relevant stimulus value, allowing some insight into the contributions of both stimulus and response repetition. In addition, a measure of switching cost relatively uncontaminated by repetition benefits can be gleaned from these analyses. By focusing solely on those trials where the two responses are made with nonhomologous effectors (and thus involve different stimuli), one can compare latencies on task 2 conditions where the set remains the same to those where the set changes.

Figure 17.3 summarizes the key findings of these analyses. Consider first the results for the split-brain patient. None of the main effects or interactions was significant. While there is a trend for J.W.’s responses to be faster when the two tasks require successive responses with homologous fingers, this difference was not reliable: $F(1, 4) = 3.8, p = 0.12$. Focusing on the uncontrolled measure of switching cost (the right side of each panel in figure 17.3), his mean latencies for same and differ-

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**Figure 17.2** Mean response latencies for the two tasks as a function of stimulus onset asynchrony (SOA) in experiment 1.
same in both visual fields. We suspect that this effect is due to an interfield stimulus repetition benefit, although these trials also entail successive responses with homologous fingers.

One final assay of cross talk between the two tasks centers on the value of the irrelevant dimension for task 1. Although the subjects were aware of the relevant dimension for task 1, the value on the irrelevant dimension was one of the possible targets for task 2. Thus a different form of repetition effect is possible on the switch trials. For example, when task 1 is color, blue square followed by square would involve a repetition on the response and value of the shape dimension. Blue triangle followed by triangle would involve a repetition on the value of the shape dimension, but here the two successive responses would involve nonhomologous responses. In the former case, color and shape are consistent in terms of their S-R mapping (i.e., both blue and square are mapped to the index finger), and in the latter, the color and shape are inconsistent. To determine whether there was an effect of filtering the irrelevant dimension for task 1 (see also, Goschke, chap. 14, this volume), we compared latencies on trials where the value on the irrelevant dimension was consistent with the target value for task 1 to those on trials where the value on the irrelevant dimension was inconsistent with the target value. The variable “filter” (consistent, inconsistent) was added to the ANOVAs reported for the repetition effects, analyzed here in terms of its effect on both the first and second responses.

Effects of filtering on RT1 were minimal and nonsignificant for all of the participants, including J.W. On average, consistent trials were responded to 9 msec faster than inconsistent for the controls and 7 msec slower for J.W. However, the consistency of the values of stimulus 1 influenced the latencies to stimulus 2 for R.I., who was faster on RT2 when the two values of stimulus 1 were consistent: \( F(1, 6) = 10.7, p < 0.02 \). The means for the other two controls were in the same direction. Thus the controls appear to show another source of interference from task 1 to task 2. When values for stimulus 1 are inconsistent (in terms of their S-R mapping for task 2), slower responses are observed to stimulus 2. Importantly, the value on the irrelevant dimension for task 1 did not influence the magnitude of the switching cost.3

The accuracy data were, in general, in accord with the latency results (table 17.1, left half). The tasks were challenging for J.W., as both responses were correct on only 73% of the trials. On task 1, J.W. responded correctly on 88% of the trials. For task 2, his performance dropped to 80%. Although the mean error rate appears higher for J.W. on switch trials, neither the main effect nor the interaction approached significance (both \( F < 1 \)). He did make more errors as SOA increased on task 2, with 90%, 83%, 95%, and 64% correct across the four SOAs. It is not clear why his performance was so poor at the 1,000 msec SOA. The short reaction times in this condition suggest a speed-accuracy trade-off, perhaps reflecting a
Table 17.1  Accuracy across the Four Stimulus Onset Asynchronies as a Function of Task Switching for Experiments 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Experiment 1</th>
<th>Experiment 2</th>
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<tbody>
<tr>
<td></td>
<td>50</td>
<td>150</td>
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<tr>
<td><strong>Callosotomy patient J.W.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same RT1</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>Switch RT1</td>
<td>0.88</td>
<td>0.83</td>
</tr>
<tr>
<td>Same RT2</td>
<td>0.96</td>
<td>0.85</td>
</tr>
<tr>
<td>Switch RT2</td>
<td>0.83</td>
<td>0.81</td>
</tr>
<tr>
<td><strong>Control A.L.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same RT1</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Switch RT1</td>
<td>0.89</td>
<td>0.95</td>
</tr>
<tr>
<td>Same RT2</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>Switch RT2</td>
<td>0.97</td>
<td>0.91</td>
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<tr>
<td><strong>Control M.S.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same RT1</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>Switch RT1</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>Same RT2</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>Switch RT2</td>
<td>0.84</td>
<td>0.77</td>
</tr>
<tr>
<td><strong>Control R.I.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Same RT1</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>Switch RT1</td>
<td>0.98</td>
<td>0.95</td>
</tr>
<tr>
<td>Same RT2</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td>Switch RT2</td>
<td>0.84</td>
<td>0.91</td>
</tr>
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difficulty in withholding the second response for a long interval after the first response.

Overall, the control subjects responded correctly to both stimuli on 89% of the trials. No significant effects were observed in the accuracy data for task 1. On task 2, a main effect of set was found for R.I.: F(1, 6) = 60.5, p < 0.001; and M.S. an interaction of showed set and SOA: F(3, 18) = 5.8, p < 0.01. In both cases, accuracy declined when the set changed, in correspondence with the latency data. In all cases, there is no indication of a speed-accuracy trade-off.

In summary, experiment 1 provides further insights into changes in multitask performance that occur after callosotomy. Across a variety of measures, the split-brain patient J.W. failed to show any sign of cross talk between two tasks, one lateralized to the right hemisphere and the other to the left. These findings extend those reported in Ivry et al. 1998, where J.W. was found able to maintain inconsistent S-R mappings within each hemisphere. In the current study, J.W. exhibited neither a task-switching cost on task 2, nor repetition effects across the hemispheres, nor any costs associated with processing the irrelevant dimension of stimulus 1. Thus his ability to maintain separable S-R mappings is not limited to the spatial domain, and holds even when the task-relevant S-R mapping for the second response fluctuates from trial to trial.

As in the other PRP studies with split-brain patients, J.W. continued to exhibit a pronounced PRP effect. Consistent with the findings of Ivry et al. 1998, the PRP effect after callosotomy appears to be quite different from that observed in healthy control participants. We expect that the PRP effect for J.W. results from a different brain organization than that seen in the control. The number and organization of the tasks, the nature of the task, or even the task instructions, reflects the operation of a later bottleneck associated with response execution, or both.

While the control subjects also follow these generic instructions, their performance suffers from task-specific sources of interference: they exhibit task-switching costs as well as other signs of cross talk between the two tasks. By applying the PRP logic to a task-switching experiment, we were able to examine the locus of interference. The patterns of additivity and overadditivity indicate that the costs associated with changing set are not related to processes involved in perceptual identification, but rather arise at a later stage of processing, one likely involved in the retrieval of the task-relevant S-R mappings or the selection of the appropriate response codes. Previous task-switching studies have typically entailed a single response system for both tasks (e.g., the right hand with a 4:2 mapping). The current study demonstrates similar costs when the two tasks are associated with different hands (see also Rogers and Monsell forthcoming). Presumably, this reflects the overall state of these response processes, at least when the callosal fibers are intact.

The hybrid task used in experiment 1 combined elements of task switching with the PRP paradigm. Although our focus was on the performance of the split-brain patient, this manipulation also proved insightful in terms of the performance of the control participants, specifying the locus of interference associated with task switching. The results of experiment 1 suggest a late stage of interference: for all of the control subjects, the switching effect was either additive or overadditive with SOA. This points to a locus of interference associated with response preparation, selection, or initiation (McCann and Johnston 1992; Ivry et al. 1998). Such a hypothesis is consistent with the notion that task-switching costs are associated with the retrieval and instantiation of new S-R mappings.

**Experiment 2**

To test this hypothesis, we conducted a second experiment with the same pair of tasks as in experiment 1, except that two stimuli were now presented along the vertical meridian. The first-task stimulus was presented above fixation and, after a variable SOA, the second-task stimulus was presented below fixation. We expected that each stimulus would be available to both hemispheres. If some or all of the various costs observed for
the controls in experiment 1 were due to intermingling of stimulus information, then we should observe these in J.W. On the other hand, because the results of experiment 1 suggested that task switching produced interference at a later stage of processing, we expected again to find no switching cost for J.W.: the successive responses were to be made with different hands, and we assumed the S-R mappings for each hand would still be restricted to the contralateral hemisphere.

**Subjects** J.W. and the same three age-matched control subjects as in experiment 1 were tested.

**Procedure** The only modification to the procedure was in the placement of the stimuli. On each trial, two stimuli were presented, a colored triangle or square above or below fixation followed by one of four univalent stimuli below fixation. The center-to-center distance between the fixation cross and the stimuli was 4.2 degrees of visual angle. The participants were instructed to respond to the upper stimulus with the right hand, and to the lower stimulus with the right. The stimuli were presented for only 200 msec to discourage eye movements, and the cross was always present to provide a fixation marker.

Each subject completed eight test blocks, four in which the relevant dimension for task 1 was color and four in which the relevant dimension was shape. For all blocks, the second-task stimulus could be either a target shape or color, with a neutral value (circle or white) used for the irrelevant dimension. The instructions were as in experiment 1 with special emphasis now given to respond first to the upper stimulus. J.W. was tested six months after completing experiment 1, whereas the control participants were tested only a day or two after completing experiment 1.

**Results and Discussion** Overall, the pattern of results was similar to that observed in experiment 1. Presenting the stimuli at the vertical meridian, and thus making them accessible to both hemispheres, was not sufficient to induce interference between the two tasks for the split-brain patient. Figure 17.4 presents the latency data for RT1 and RT2, collapsing over the color and shape conditions. For all of the participants, RT2 decreases with SOA. This is the only variable that is significant for J.W. In contrast, all of the controls show an effect of set—R.I.: F(1, 6) = 127.3, p < .001; M.S.: F(1, 6) = 11.5, p < .05; A.L.: F(1, 6) = 376.9, p < .001. The interaction of set and SOA is significant for two of the control participants—R.I.: F(3, 18) = 6.6, p < .01; M.S.: F(3, 18) = 7.8, p < .01. As in experiment 1, the interaction is one of overadditivity, with the switching cost most evident at the shortest SOA.

Whereas J.W.'s latencies on task 1 did not differ across conditions, all of the controls showed an effect of SOA—R.I.: F(3, 18) = 5.0, p < .05; A.L.: F(3, 18) = 8.8, p < .001; or an of set and SOA interaction—M.S.: $F(3, 18) = 7.8, p < .01$. The controls responded more quickly to the first stimulus at the long SOAs.

J.W. did not show evidence of cross talk between the two tasks on the additional measures of multitask interference (figure 17.5). There was no evidence of either response or set repetition benefits for RT2: $F(1, 7) < 1$. Nor did J.W. show any filtering effects related to the value of the irrelevant dimension for stimulus 1 on either RT1 or RT2: $F(1, 7) = 1.9, p = .21$; $F(1, 7) < 1$, respectively. The interaction of response relationship and set was reliable for two of the controls—R.I. F(1, 6) = 12.3, $p < .05$; A.L.: $F(1, 6) = 18.9, p < .01$. For R.I. and A.L., the interaction indicates that the switching cost was greatest when the two responses involved homologous effectors. Nonswitch trials here correspond to trials in which the task-relevant stimulus value remained identical across the two hemifields. For M.S., only the main effect of response relationship approached significance: $F(1, 6) = 5.3, p = .06$. 

![Figure 17.4 Mean response latencies for the two tasks as a function of stimulus onset asynchrony (SOA) in experiment 2.](image)
the performance of the split-brain patient and that of the controls. Whereas J.W.’s accuracy was relatively constant across SOA, the control subjects became more accurate as SOA increased, especially on RT2—R.I.: F(3, 18) = 5.9, p < 0.05; M.S.: F(3, 18) = 12.9, p < 0.001.

The results of experiment 2 provide new evidence that the costs observed in task-switching experiments are associated with stages of processing closely linked to response processes rather than to perceptual analysis. Even though the stimuli were presented along the vertical meridian, the performance of the split-brain patient again indicated that the two tasks were effectively segregated. While we assume that each hemisphere had access to information related to both the upper and lower stimuli, it nonetheless appears that the processing of each stimulus is essentially restricted to the hemisphere required for generating the responses; there was no evidence that the stimulus or response codes for the two tasks interacted.

17.4 IMPLICATIONS FOR MODELS OF EXECUTIVE CONTROL

Task-switching experiments have been used to study control processes associated with the coordination of performance in multitask situations. The concept of task switching has been used to capture the idea that our behavior is not simply exogenously guided, but also reflects the interaction of the stimulus information with our internal goals. Indeed, it is this interaction that allows human behavior to be so flexible and adaptive (see Gotschke, chap. 14, this volume). Although we can exert some control over which information to attend to, and respond in a way that will help achieve our current goals, this control comes at a cost. Adopting a particular task set limits the speed with which we can alter our behavior should the environmental conditions suddenly change, or should the task requirements mandate a new set of candidate actions. This cost has been interpreted as reflecting limitations in our ability to integrate perceptual, cognitive, and response processes to meet the behavioral requirements of the moment (Allport, Styles, and Hsieh 1994; Rogers and Monsell 1999; Rogers et al. 1996).

An important component operation of task switching involves the establishment and maintenance of S-R mappings. In our previous studies (Franz et al. 1996; Ivy et al. 1998), we observed that callosotomy patients fail to exhibit interactions between spatial codes represented in each hemisphere. The current study was designed to examine whether the lack of interaction would also be evident in a nonspatial task as well as under conditions in which the S-R mappings, at least in one hemisphere, had to be dynamically reorganized from trial to trial.

As expected, the neurologically healthy control participants exhibited numerous manifestations of interference between the two tasks: intermanual task-switching costs, repetition effects, and filtering costs associated with the value of the task-irrelevant dimension of the first stimulus.
While stimulus repetition benefits were found in a few situations, the results suggest that the prominent source of interference was associated with processes involved in response preparation and selection. In particular, the PRP analysis indicated that the effect of task switching was additive or overdissociative with the interval between the two stimuli, a pattern indicative of a source of interference downstream from processes associated with perceptual identification. We have argued that the task-switching interference arises from the operation of processes involved in the establishment of task-relevant S-R mappings, a hypothesis similar to the response selection bottleneck hypothesis promoted by Pashler (1994, chap. 12, this volume).

The fact that the task-switching cost is found even when the successive responses are performed with different hands indicates that this operation occurs at a relatively abstract level (see also Rogers and Monsell forthcoming). Although consistent with previous findings in the motor literature that, at higher levels, S-R codes are not linked to particular effectors, this finding is better conceptualized in terms of a goal-based representation (e.g., Hommel 1993; MacKay 1982). The unity of goal-oriented representations would provide a locus for the interference between the two tasks. Nonetheless, it seems likely that under certain conditions, different sets could be associated with distinct effectors. For example, when driving, we do not find ourselves pushing on the steering wheel when we go to engage the clutch. In this condition, there does not appear to be any cross talk between the actions produced by the hands and feet. On the other hand, the sets associated with effector systems in such situations are well learned and relatively invariant. In task-switching experiments, the context and thus mapping are in constant flux, placing high demands on control processes (Norman and Shallice 1986). We expect that the cost of switching set would be as great within an effector as between effectors in such conditions.

In sharp contrast to the control subjects, the split-brain patient did not exhibit any evidence of task-specific interference in the two experiments. He was just as fast to respond to the second stimulus when the task-relevant dimension changed as when the task-relevant dimension remained the same. Moreover, he did not exhibit repetition effects between the two hemispheres, nor did he show any costs associated with the value of the task-irrelevant dimension for the first stimulus. These results suggest that processes involved in the establishment and maintenance of S-R codes can be independently supported in the two cerebral hemispheres. The interhemispheric task-switching costs found in the normal participants are likely to involve interactions across the corpus callosum rather than to arise from a single control process localized to one hemisphere. Interestingly, the lack of cross talk was also evident even when the stimuli were presented bilaterally in experiment 2. This finding provides additional evidence that the source of interference from changing set is linked to response processes rather than to perceptual processes.

The present experiments provide specificity to the putative operations underlying executive function. An important component of flexible behavior is the ability to create transient representations of S-R codes to achieve task-relevant goals. The costs associated with task switching reflect the fact that, when the task changes, new goals must be instantiated, leading to the activation of new S-R codes. These codes, at least in normal individuals, are generically available to all response systems. Although this may create interference when the task requirements change, the activation of abstract response codes should be adaptive in promoting goal-oriented behavior.

NOTES

This work was supported by National Institutes of Health grants NS30256 and NS17778. We are grateful to Kristi Hitt, Emily Levitas, Fredrik Nilson, and Michael Miller for their assistance in collecting data and preparing this chapter, and to Michael Gazzaaniga for his many insightful comments.

1. We also tested 12 college-age controls for experiment 1 and 19 controls for experiment 2. The pattern of results for these groups was quite consistent with that of the age-matched controls with the exception that the switching costs were smaller for the college students in experiment 2.

2. We also tested a fourth age-matched control subject, H.A. Like the split-brain patient, J.W., this person did not exhibit a task-switching cost, although his null result is likely due to very different reasons. H.A. was extremely slow in performing task 2, with mean latencies collapsed over SOA of 1,765 msec for the same-set trials and 1,780 msec for the different-set trials. Indeed, even at the longest SOA of 1,000 msec, mean latencies for H.A. were slower than for any of the other participants at all SOAs. Given that H.A. did not appear to heed the instructions to respond rapidly, we do not report his data in the main text. Such data suggest, however, that control subjects can avoid a task-switching cost in this task only by making the second response very slowly.

3. There are other ways in which repetition effects can be analyzed with these data. For example, on nonswitch trials, homologous responses entailed the repetition of the relevant feature value (e.g., with shape relevant for both tasks, a blue square would be followed by a square), and nonhomologous responses precluded the repetition of the relevant feature (e.g., blue square followed by triangle). That is, the relevant feature for task 2 was always present in the stimulus for task 1 when the two tasks required homologous responses and never present when the two tasks required nonhomologous responses. In contrast, for the switch trials, homologous responses included repetitions and nonrepetitions of second-task-related features with equal frequency. To assess the importance of different repetition factors (stimulus, response, set), however, would require more than two values for each dimension.

REFERENCES


