Journal of Experimental Psychology:
Human Perception and Performance
1998, Vol. 24, No. 2, 463–480

0096-1523/98/$3.00

The Psychological Refractory Period Effect Following Callosotomy: Uncoupling of Lateralized Response Codes

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A callosotomy patient was tested in 2 dual-task experiments requiring successive speeded responses to lateralized stimuli. The patient showed a robust psychological refractory period (PRP) effect. Three aspects of the data indicate that, unlike for the control participants, the PRP effect for the split-brain patient should not be attributed to a response selection bottleneck. First, the patient did not show an increase in reaction time (RT) when the 2 tasks required responses from a common output system compared with when different output systems were used. Second, inconsistent stimulus–response mappings for the 2 tasks increased RTs for the control participants but had minimal effect on the performance of the split-brain patient. Third, the consistency manipulation was underadditive with stimulus onset asynchrony but was additive or overadditive for the normal participants. These results suggest that the persistent PRP effect following callosotomy should be attributed to a bottleneck associated with response initiation, a strategy adopted to comply with the task demands, or a combination of these factors.

People are generally quite adept at performing multiple tasks during the same period of time. A skilled driver can navigate a curved roadway while listening to the radio and dialing a friend on a cellular phone. Or, when washing the evening dishes, one is able to manipulate the dirty plates and glasses while listening to the evening news. The ability to execute multiple tasks is not limited to situations that require monitoring information across different perceptual channels. The catcher on a baseball team must track the ball thrown by the pitcher while peripherally monitoring the movement of the opposing base runners to prevent them from stealing a base.

Although our success in jointly performing multiple tasks is impressive, this ability is also limited. Some limitations can be attributed to structural limitations in our perceptual and motor apparatus (Meyer & Kieras, 1997a, 1997b; Meyer et al., 1995). The need to foveate detailed visual information constrains our effective field of view. Actions of the arms and legs are coordinated so that postural stability is maintained. Other limitations appear to result from limited cognitive resources. Some of these limitations may reflect individual differences in skill. Unlike the expert, the novice driver would be petrified if asked to remove a hand from the steering wheel to answer a cellular phone. A second source of limitation may result from shared executive processes that are required to coordinate performance in multiple-task situations (Meyer & Kieras, 1997a, 1997b; Meyer et al., 1995). These constraints may persist even with highly practiced research participants (e.g., Gottsdanker & Stelmach, 1971; Karlin & Kestenbaum, 1968; reviewed in Pashler, 1994).

Dual-task studies have been used by some researchers as a tool to study general capacity limitations. An alternative approach has been to use the dual-task paradigm to identify a specific locus or loci of interference. An underlying assumption here is that any particular task involves a limited set of internal operations. The set of operations varies from task to task, and a particular pair of tasks may invoke overlapping sets. Some of these operations may be executed in parallel. As such, one would expect minimal dual-task interference to arise at these stages. Other operations may require access to mechanisms that can only operate on input from one task at a time.

It is these latter operations that constitute processing bottlenecks. The psychological refractory period (PRP) has been hypothesized to reflect the existence of a processing bottleneck. In the PRP paradigm, participants are required to perform two tasks in rapid succession on each trial. For example, the first response might require the participants to judge whether a circle is located above or below a central position, and the second task might entail a lexical decision

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This research was supported by National Institutes of Health (NIH) Grant NS30256 and NIH Fellowship NS09318. Informed consent was obtained from all participants, and the data were coded to protect the anonymity of the participants.

We thank Geoffrey Rowland and Naomi Shimizu for their help in collecting the data and Dave Meyer, Ritske De Jong, and Tom Carr for their comments in the reviewing process.

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on a string of letters. Participants are instructed to respond as fast as possible on both tasks, subject to the constraints that their initial response should be to the first stimulus and that the two responses should be successive, rather than grouped. The stimulus-onset asynchrony (SOA) between the presentation of the first stimulus (e.g., the circle) and the presentation of the second stimulus (e.g., the letter string) is varied. Across a wide range of situations, response times on Task 2 have been found to be inversely related to SOA. This delay is referred to as the PRP (Welford, 1952).

Extensive work with the PRP paradigm has been devoted to identifying processing stages that produce a bottleneck. One proposal has been that response selection constitutes a critical bottleneck across a range of task pairings (reviewed in Pashler, 1994). In terms of this view, the PRP effect arises because response selection for Task 2 must be delayed until this operation is completed for Task 1. In support of this hypothesis, Pashler and Johnston (1989) found that manipulating the intensity of Stimulus 2 was underadditive with SOA, whereas repeating Stimulus 2 over successive trials was additive with SOA. The underadditivity in the former case is consistent with the hypothesis that intensity affects perceptual processing (e.g., Miller, 1979); the extra time needed to process a dim Stimulus 2 could occur while Task 1 is still in the bottleneck stage. The additivity in the latter case is consistent with the hypothesis that the benefits of repeating a stimulus (and a response) are primarily due to enhanced efficiency in response selection (Kornblum, 1969). Although the repetition effects were small, further evidence that manipulations which influence response selection processes produce additive effects with SOA were reported by McCann and Johnston (1992), who varied stimulus–response (S-R) compatibility.

Alternatively, Meyer and his colleagues (Meyer & Kieras, 1997a, 1997b; Meyer et al., 1995) have advocated a more flexible position, arguing that the bottleneck may change as a function of structural limitations (e.g., the eyes can only look at one place at a time), experimental instructions, and participants' strategy and experience. This approach is consistent with findings showing that manipulations thought to influence response selection do not always produce additive effects with SOA and that there are considerable individual differences within a given experiment (see Meyer et al., 1995). It has also been argued that there may be multiple bottlenecks (e.g., De Jong, 1993). For example, a central bottleneck may limit the operation of a response selection process, with a second bottleneck occurring when responses compete for a common output system (see also Keele, 1973).

A priori, it is reasonable to suppose that dual-task interference should be greater when the tasks require similar responses. In support of this, McLeod (1977) observed considerable disruption during manual tracking when manual responses with the nontracking hand were required for a secondary tone-discrimination task. In contrast, minimal interference was found when the tones were responded to vocally (see also McLeod & Posner, 1984).

However, Pashler (1990) argued that the effect of response modality in McLeod's studies was primarily due to the fact that the order of stimuli varied unpredictably. When task order was specified in a set of PRP studies, Pashler (1990) observed a residual response modality effect (see also De Jong, 1993). Manual responses on Task 1, a letter identification task, were slower by over 100 ms when Task 2 also required a manual response compared with when Task 2 required a vocal response. As important, a substantial PRP effect was present in both the manual–manual and the manual–vocal conditions. This was interpreted as demonstrating that the response selection bottleneck operated independent of stimulus modality or response mode. Indeed, Pashler (1990) argued that the effect of Task 2 on Reaction Time (RT) 1 further reflected the limitations of processes involved in response selection. An additional cost may be associated with keeping track of the two different S-R mappings when these mappings were both associated with manual responses.

The PRP paradigm has recently been extended to neuropsychological research. In the laterality literature, it has been proposed that each hemisphere is endowed with separate resource pools, with dual-task interference being a function of the cerebral distance separating two tasks (Friedman & Polson, 1981; Kinsbourne, 1981; Kinsbourne & Hicks, 1978). By this logic, less interference should be expected when the two tasks are dependent on different hemispheres in comparison with when the tasks invoke the same hemisphere. Contrary to this prediction, Pashler and O'Brien (1993) found similar PRP effects for tasks selected to tap into different hemispheres and for tasks expected to depend on a single hemisphere. From these findings, Pashler and O'Brien concluded that the PRP effect reflected a cognitive operation that was shared by both hemispheres.

To further explore hemispheric interactions in dual-task performance, Pashler et al. (1994) tested "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 participants indicated the position of this 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 three callosotomy patients.

The persistence of the PRP effect in callosotomy patients stands in contrast to other studies showing reduced interactions between the two hemispheres on both the perceptual and the response end of processing. A number of studies have shown that perceptual analysis can occur relatively independently in the two hemispheres of split-brain patients (Holtzman & Gazzaniga, 1985; Kingstone, Enns, Mangun, & Gazzaniga, 1995; Kingstone & Gazzaniga, 1995; Luck, Hillyard, Mangun, & Gazzaniga, 1989; Seymour, Reuter-Lorenz, & Gazzaniga, 1994). For example, although these patients were able to make same–different judgments when two stimuli were presented within the same visual field, performance was essentially at chance on between-field comparisons (Seymour et al., 1994). Similarly, when a response based on bilateral displays can be based on a single item, perceptual capacity limitations indicate a duality of processing resources in callosotomy patients. The time required to find a conjunction target in a visual search task is dependent on the number of items within each hemifield for these patients rather than, as is found with "normal" individuals, being a function of the number of items in the entire display (Kingstone et al., 1995; Luck et al., 1989).

In terms of motor control, Franz, Eliassen, Ivry, and Gazzaniga (1996) have observed a selective loss of interference in bimanual movements produced by split-brain patients. In one study, participants were asked to simultaneously draw two figures, one with each hand. In some conditions, the movements were spatially consistent (e.g., both movements parallel to the frontal plane); in others, the movements were spatially inconsistent (e.g., one movement parallel to the frontal plane and the other orthogonal to the frontal plane). Neurologically intact participants had great difficulty in the latter condition: Reaction and movement times increased dramatically, and they showed significant deviations from the target figures. Neither problem was observed in the split-brain patients: They showed no difference between the two conditions.

However, analysis of the phase relations between the two movements revealed an important dissociation. The movements in the split-brain patients remained temporally coupled: The right and left hands moved in a synchronous fashion similar to what is seen in normal individuals. Thus, it appears that separate neural mechanisms underlie spatial and temporal coupling (Franz et al., 1996). The spatial uncoupling was attributed to the elimination of cross-talk between the spatial plans for the two movements. Such cross-talk might reflect a distributed motor-planning system in which abstract motor plans (i.e., reach forward to pick up a glass of water) are translated into specific movement trajectories (i.e., with the left hand). A competitive process could ensure the selection of one gesture to achieve a particular goal out of the large set of possible gestures (see Ivry, 1997; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995).

Pashler et al. (1994) inferred that the persistent PRP effect in callosotomy patients provided further evidence of a central bottleneck associated with postperceptual response selection. This conclusion is in accord with the findings cited above in suggesting that these patients are capable of performing independent perceptual analysis within each hemisphere. However, the fact that split-brain patients can plan and produce incompatible bimanual movements (Franz et al., 1996) does not appear to be consistent with the claim of an intact unitary response selection bottleneck.

We designed the current studies to examine this apparent contradiction. To this end, we tested a split-brain patient on a series of PRP tasks. By making the tasks more distinct than those used in Pashler et al.'s (1994) study and by manipulating the similarity of response requirements, the generality of a PRP effect following callosotomy can be established. Moreover, by comparing the patient with control participants, we can identify similarities and differences in the patterns of dual-task interference. On the basis of Franz et al.'s results (1996), we expected to observe less interference related to response competition than is found in normal participants.

Experiment 1

Pashler et al. (1994) combined two spatial discrimination tasks that seem to maximize potential sources of interference. Split-brain patients first judged the vertical position of a stimulus presented in the left visual field and then made an identical discrimination for a stimulus in the right visual field. In addition, both responses were performed manually with the index and middle fingers of each hand. In Experiment 1 we tested whether the observed PRP effect was dependent on the need to share processing resources required for spatial discriminations, programming manual responses, or both.

We sought to make the perceptual tasks as distinct as possible while staying within the visual domain, the modality for which lateralized segregation of information is best established. Task 1 was similar to that used by Pashler et al. (1994). A circle was presented in the left visual field, and the participants were asked to indicate the spatial position of the circle by responding with one of two fingers of the left hand. For Task 2, we used a lexical decision task. A string of letters was shown in the right visual field, and the participant indicated whether or not the string spelled an English word. In separate blocks of trials, two types of responses were compared. In one condition, responses on Task 2 were made manually by pressing a button with the right hand. In the other condition, responses on Task 2 were made vocally to indicate the perceived lexical status of the stimulus.

Method

Participants

A detailed description of the patient, JW, is provided in Gazzaniga, Nass, Reeves, and Roberts (1984). Briefly, JW, a 41-year-old right-handed man, underwent a callosotomy operation in 1979 for treatment of intractable epilepsy. The operation involved all of the fibers of the corpus callosum and the posterior commissure (MRI verified). Postoperatively, JW demonstrated the capacity to comprehend language in both the left and the right hemispheres, although speech was lateralized to his left hemisphere. Seizure activity has been minimal for the past 15 years, and the patient has made an excellent recovery. He shows some clumsiness in movements with the left hand but is able to use both of his hands in his daily activities. JW has participated in psychological studies on a regular basis for the past 15 years.

Two groups of control participants were tested. The first group comprised four male participants who were comparable in age to JW (aged 39, 40, 42, and 43). These participants completed the same protocol as JW. The second group was drawn from the undergraduate participant pool maintained by the University of California, Berkeley ($n = 9$). None of the control participants in either the age-matched (AM) or the college-age (CA) groups reported any history of neurological or psychiatric disorders. All were right-handed. The AM control participants and JW were paid for participating in the experiment. The CA participants received course credit.

Procedure

Each trial consisted of the following series of events. First, a small, filled circle was presented at the center of the display. This served as both a warning signal and as a fixation point. After an 800-ms delay, a large, empty circle appeared in the left visual field, located above or below the horizontal meridian. The circle was presented for 50 ms. Responses were made with the left hand, with the middle and index fingers used to respond to the above and below locations, respectively.

After a variable SOA, a string of letters appeared in the right visual field. The letters were presented for 200 ms.[1] Participants were required to indicate whether the letters formed a word or not. For the manual condition, the responses were made with the index and middle fingers of the right hand for the *yes* and *no* responses, respectively. For the vocal condition, the participants were instructed to say "yes" or "no." A voice-activated relay measured the latencies of the vocal responses, and an experimenter wrote down the response for off-line verification of accuracy.

In all conditions, participants were instructed to respond as rapidly as possible on both tasks while attempting to minimize errors. The instructions further emphasized that RT on the spatial discrimination task should be given primary emphasis. Feedback indicating the total number of errors on both tasks was provided at the end of each block.

The onset of the spatial stimulus and letter string was separated by one of four SOAs: 50, 150, 400, and 1,000 ms. Each SOA occurred equally often for all combinations of two spatial positions (above or below) and lexical type (high-frequency words, low-frequency words, and nonwords). Given this distribution, the letter string formed a word on two thirds of the trials.

The data were collected over two sessions for the patient and for the AM control participants. Within each session, participants completed a pair of test blocks with one response pairing (e.g., manual–vocal) and then another pair of test blocks with the other response pairing (manual–manual). The test blocks were preceded by practice blocks of 48 trials, first with each task tested alone and then in combination. Each test block consisted of 96 trials. Testing with the two response pairings was separated by a 30-min break. The order of testing was reversed for the second session. For example, if the participant had been tested on manual–vocal first in Session 1, Session 2 began with manual–manual. Each session lasted approximately 2 hr.

The CA control participants were tested in a single session. Half of the participants began with the manual–manual condition, completing one practice block and two test blocks. Then they completed a second practice block and two test blocks in the manual–vocal condition. The order of conditions was reversed for the other half of the participants.

Stimuli and Response Collection

The experiment was controlled by a PC computer system. Manual responses were recorded from response keys mounted on wooden response boards; vocal responses were detected following activation of a voice-activated relay. A programmable input–output card (Advantech PCL-712) was used to control the timing of the stimulus events and to detect responses on the response systems with an accuracy to the nearest millisecond.

The stimuli were displayed on a VGA monitor. The background of the screen was black, and the fixation point, spatial target, and letter string were white. The fixation point subtended a visual angle of 0.5° and was positioned at the center of the display. The spatial target for Task 1 was a circle with a diameter of 1.5°. The circle was displaced to the left of the fixation point by 3.3° and was shifted 2.4° above or below the horizontal meridian. The stimuli used for Task 2 were strings of four letters. The entire string of letters subtended a visual angle of 3.3°, with the first letter positioned 3.3° to the right of the fixation point.

There were four groups of letter string stimuli: two word sets (high and low frequency) and two nonword sets (pronounceable and nonpronounceable). The high- and low-frequency words were presented on one third of the trials each, and nonwords were presented on the remaining one third of the trials. For the split-brain patient and the controls tested on the full protocol, the strings were nonpronounceable, consisting of four consonants. For the CA control participants, the stimuli were pronounceable nonwords. The primary findings in this study did not vary as a function of word type, and thus we did not report the analyses of this variable.[2]

Results and Discussion

Figure 1 presents the response latencies for Tasks 1 and 2 for the split-brain patient (top), the AM controls (middle), and the CA controls (bottom). The data are from trials in which both responses were correct. Trials were excluded when the participant was incorrect on either response or failed to make both responses, or when either of the latencies was excessively long. For JW and the AM control participants, RTs faster or slower than 3 *SD*s of the individual mean latencies were excluded. For the CA participants, any trials with latencies greater than 1,600 ms were excluded. By these criteria, the percentages of excluded trials were 4.0% for the patient, 5.1% for the AM controls, and 4.2% for the CA control participants. Approximately half of these were due to the failure of the participants to respond to one or both of the stimuli.

To statistically analyze the results, analyses of variance were conducted for the split-brain patient for each dependent variable (RT1, RT2, errors). For these analyses, the mean RT for each condition was calculated for trials in which the responses on both tasks were correct. Blocks were treated as a repeated measure, and the variables for the analyses were response mode (manual or vocal) and SOA. Similar analyses were also performed separately for each of the AM control participants. However, for these participants and for the CA

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[1] The short exposure durations were used to minimize the likelihood that participants would fail to maintain fixation. Eye movements were monitored for JW and occurred on very few trials. Eye movements were not monitored for the control participants, although they were instructed to maintain fixation on the central circle that remained on the screen for the duration of the trial.

[2] JW completed an additional session in which the pronounceable nonwords were used for four blocks of dual-task trials with a manual–manual response pairing. Two of the AM control participants completed two additional sessions with the pronounceable words, totaling six blocks with the manual–manual pairing and six blocks with the manual–vocal pairing. The results with these stimuli were essentially identical to those obtained in the basic experiment. For example, in the critical comparison of RT1 (see Task 1 results for Experiment 1), the control participants showed an advantage on RT1 of 58 ms and 131 ms on the manual–vocal blocks compared with their RTs on the manual–manual blocks. No systematic differences were seen on RT2 or errors.

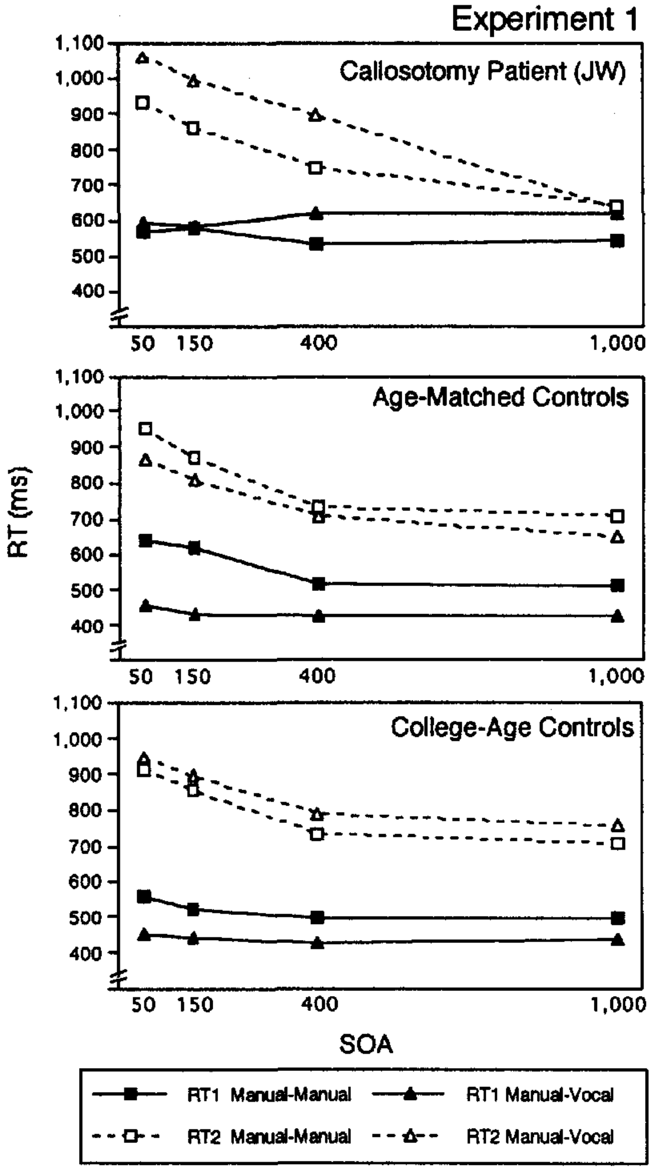

Figure 1. Response latencies for Task 1 (spatial position) and Task 2 (lexical decision). Reaction time (RT) is plotted as a function of stimulus onset asynchrony (SOA) for the patient JW (top), the age-matched controls (middle), and the college-age controls (bottom). Solid lines represent Task 1, and dotted lines represent Task 2. Squares represent manual–manual conditions, and triangles represent manual–vocal conditions.

controls, group analyses were performed to simplify the presentation of the results. Deviations between the group and individual analyses for the AM controls are noted.

Task 2 Response Latencies

The primary question to be addressed was whether the basic PRP effect is obtained with disparate tasks. A PRP effect is readily apparent in all three parts of Figure 1. The mean RT for Task 2 is inversely related to the SOA, implying greater interference between the two tasks as the delay between the two stimuli is reduced. The effect of SOA was highly significant in all analyses: for JW, $F(3, 9) = 172.44$, $p < .0001$; for AM controls, $F(3, 9) = 15.64$, $p < .001$; for CA controls, $F(3, 24) = 47.84$, $p < .0001$. These results indicate that the PRP effect is manifest in a callosotomy patient even when the two tasks involve different forms of perceptual analysis and separate output systems.

This conclusion is further supported by the slightly greater magnitude of the PRP effect in JW than in the AM controls. For JW, the differences in RT2 between the shortest and the longest SOA are 285 ms and 428 ms for the manual and vocal conditions, respectively. The interaction between SOA and response mode was significant, $F(3, 9) = 7.24$, $p < .01$. This effect was not observed for either the AM controls (manual difference = 258 ms; vocal difference = 254 ms) or the CA controls (manual difference = 189 ms; vocal difference = 190 ms).

The effect of response mode was not significant for either JW, $F(1, 3) = 4.81, p > .11$, or the AM controls, $F(1, 3) < 1$. For the CA controls, vocal responses on Task 2 were marginally slower than manual responses, $F(1, 8) = 4.21$, $p = .07$. Note that for the AM controls, the opposite pattern is seen in Figure 1, where manual responses appear to be slower. This was due to one participant, who was almost 300 ms slower in making manual decisions on the lexical decision task, a difference that was reliable in his individual analysis, $F(1, 3) = 29.37, p < .05$.

Task 1 Response Latencies

Similar analyses were performed on the Task 1 RT data. Note, though, that the stimuli and response mode are identical for all conditions here: The task always involved a spatial discrimination, and the responses were made manually.

Neither of the main effects was significant for the split-brain patient on the response latencies for the spatial discrimination task. However, there was a Response Mode × SOA interaction, $F(3, 9) = 11.18$, $p < .01$. When Task 2 response was vocal, RT1 increased by 29 ms from the shortest to the longest SOA. When Task 2 response was manual, RT1 decreased by 22 ms from the longest to the shortest SOA. Overall, RT1 was slower by 47 ms when this manual response was paired with a vocal response compared with when paired with another manual response.

A very different pattern of results emerged in the analyses of the control data. Both groups showed a main effect of response mode: for AM controls, $F(1, 3) = 41.28, p < .01$; for CA controls, $F(1, 8) = 35.11, p < .001$. In each case, this effect was the result of responses on the spatial discrimination task being substantially slower when the lexical decisions were made manually. Requiring a manual response on Task 2 inflated Task 1 RTs by 134 ms and 81 ms for the AM and CA controls, respectively. In contrast, JW was actually faster by 47 ms in responding on Task 1 when the second response was also manual, although this difference was not significant. These results suggest that Task 2 produced more interference on Task 1 for the control participants than it did for the split-brain patient.

This hypothesis is further supported by the findings that the response times on Task 1 for the control participants were inversely related to SOA: for AM controls, $F(3, 9) = 3.86$, $p < .05$; for CA controls, $F(3, 24) = 10.56$, $p < .001$. Moreover, this variable also interacted with Task 2 response mode: for AM controls, $F(3, 9) = 9.13$, $p < .05$; for CA controls, $F(3, 24) = 4.89$, $p < .01$. The effect of SOA on RT1 was much larger when the second response was manual than when it was vocal. When Task 2 required a vocal response, the change in RT1 from the shortest to the longest SOA was reduced: for AM controls, manual = 145 ms, vocal = 51 ms; for CA controls, manual = 55 ms, vocal = 17 ms. This pattern reflects a tendency for some control participants to group the two manual responses at short SOAs. This was especially marked in one of the AM controls. The SOA × Response Mode interaction was not significant for two of the AM controls in the individual analyses.

Errors

For all participants, almost all of the errors occurred on Task 2. This is likely due to their being required to perform a lexical decision task on briefly presented parafoveal stimuli. JW had considerable difficulty on the lexical decision task. Overall, on 24.8% of the trials, JW either made an error or failed to produce a response to one of the stimuli. It is unlikely that these errors reflect a disproportionate allocation of attention to the spatial discrimination task under the dual-task conditions, because JW's error rate on the single-task blocks with the lexical decision task was also over 25%.

The difficulty of the lexical decision task is further underscored by the overall error rates for the control groups. For the AM controls, an average of 13.3% of the trials included an error or no response; for the CA controls, this value rose to 20.3%. Within each group, error rates for individual participants were comparable to those of JW.

The distribution of errors was relatively uniform for JW. There were no significant main effects or interaction. The error rates for the control groups decreased over SOA: for AM controls, $F(3, 9) = 6.00$, $p < .05$; for CA controls, $F(3, 24) = 5.55$, $p < .01$.

Summary

Two primary findings emerged in this study. First, the results demonstrate clearly that the PRP effect remains robust following sectioning of the corpus callosum. These findings are in accord with the report of Pashler et al. (1994). Given the divergent structure of the two tasks, it can be concluded that the PRP effect following callosotomy is not restricted to situations in which the two tasks require the same form of analysis or tap into a common response system. Whether the patient's performance is limited by a bottleneck similar to that influencing normal performance is addressed in Experiment 2 and in the General Discussion section.

Second, although a PRP effect was evident in the split-brain patient, the results reveal a difference between his performance and that of the control participants on a second measure of dual-task interference. Control participants showed a substantial cost in making manual responses on Task 1 when the second task also required manual responses. This interference was manifest in two ways: Not only was there an overall slowing on Task 1 when both responses were manual, but the manual–manual interference was strongest at the shortest SOA. Indeed, some of the control participants appeared to group the two manual responses when the stimuli followed one another in close succession despite our instructions to respond to Stimulus 1 as quickly as possible.

In contrast, JW's performance on Task 1 was relatively independent of the requirements of Task 2. Thus, while he shows evidence of general interference in this PRP paradigm, he does not demonstrate this second source of interference. By definition, this second source is task-dependent: It arises with specific combinations of response channels. The callosotomy operation appears to render each hemisphere capable of selecting responses independent of the processing requirements incurred by the other hemisphere.

It might be argued that the RT1 effects for the control participants reflect the failure of these participants to heed our instructions to give precedence to Task 1. Indeed, the responses on Task 1 were consistently faster at the long SOAs. Perhaps JW did not show effects of Task 2 on RT1 simply because he (unlike the control participants) paid strict attention to the instructions and gave full precedence to Task 1. We return to this issue in Experiment 3.

Experiment 2

When performing in a dual-task experiment, participants must maintain two distinct S-R mappings, one for each task. The increase in RT1 in the manual–manual condition for control participants might reflect interference between S-R mappings when the two tasks involve the same output modality. The split-brain patient did not show this source of interference, a result consistent with the idea that the mappings for each task are isolated to a single hemisphere following callosotomy. To test this idea directly, we used a manipulation in Experiment 2 that has been shown to have a marked effect on the performance of normal individuals in dual-task situations: the degree of consistency in the S-R mappings for the two tasks.

Duncan (1979) combined two 3-choice spatial discrimination tasks and varied the mapping of the stimuli and responses. For compatible mappings, the arrangement of the fingers on the response board was aligned with the stimulus positions. For incompatible conditions, the mappings were reversed. Four conditions were created by a factorial combination of the two S-R mappings used for each hand. In this manner, Duncan was able to examine two sources of interference. First, there was the effect of compatibility. Second, there was the effect of consistency. In two of his conditions, the two S-R mappings were inconsistent with one another: One hand was assigned a compatible mapping, and the other was assigned an incompatible mapping.

As expected, responses were slower when the S-R mappings were incompatible. Of greater relevance for our purposes were the consistency effects on RT1. Response latencies on Task 1 were faster by over 100 ms when the two mappings were consistent than when they were inconsistent. This occurred regardless of whether the two mappings were both compatible or incompatible. Normal participants have great difficulty simultaneously keeping track of inconsistent response mappings.

In Experiment 2, we used a subset of the conditions tested by Duncan (1979) in a PRP paradigm. Both tasks required the participants to make two spatial discriminations by first responding to the vertical position of a stimulus in the left visual field and then responding to the vertical position of a stimulus in the right visual field. The left hand was used for responses to the left visual field stimuli, and a compatible S-R mapping was used. The right hand was used for responses to the right visual field stimuli. In half of the blocks, the mapping for the right hand was consistent with that used for the left hand; for the other half of the blocks, the right-hand mapping was inconsistent with the left-hand mapping. We did not vary the compatibility for left-hand responses to limit the testing time required of JW. In addition, in a pilot study, he had great difficulty using an incompatible S-R mapping with the left hand, perhaps reflecting the limited capacity of the right hemisphere relative to the left hemisphere.

Given the above discussion, we expected control participants to show an increase in RT1 when the S-R mappings for the two tasks were inconsistent with one another. However, it was predicted that the split-brain patient's performance on Task 1 would be unaffected by the particular mapping used for Task 2, reflecting a lack of interference between the S-R codes associated with the two tasks.

Experiment 2 can also be used to assess whether the bottleneck for the split-brain patient arises at a similar processing stage to that found for normal participants (see McCann & Johnston, 1992). Consider two scenarios depicted in Figure 2: One in which an experimental manipulation of Task 2 affects processing prior to the bottleneck, and one in which a manipulation affects processing within the bottleneck stage itself. An example of the former case might be if the perceptual analysis is made more difficult for Task 2, perhaps by decreasing the intensity of the stimulus (De Jong, 1993; Pashler & Johnston, 1989). As can be seen in Figure 2a and 2b, the effect of this manipulation is underadditive with SOA. At short SOAs, the additional processing required for the dimmer stimulus can occur during the bottleneck period for Task 1. However, at longer SOAs, this extra processing time will extend beyond the point at which the bottleneck operation can begin for the easier condition of Task 2. Thus, a task manipulation that influences processes prior to the bottleneck is most apparent at long SOAs.

In contrast, Figure 2c and 2d demonstrate that manipulations that influence processing at the bottleneck stage itself produce additive effects with SOA. The differences resulting from such a manipulation are equally potent across all SOAs. McCann and Johnston (1992) have found that manipulations of S-R compatibility produce additive effects with SOA. They argued that this pattern further supports the hypothesis that there is a central bottleneck associated with response selection.

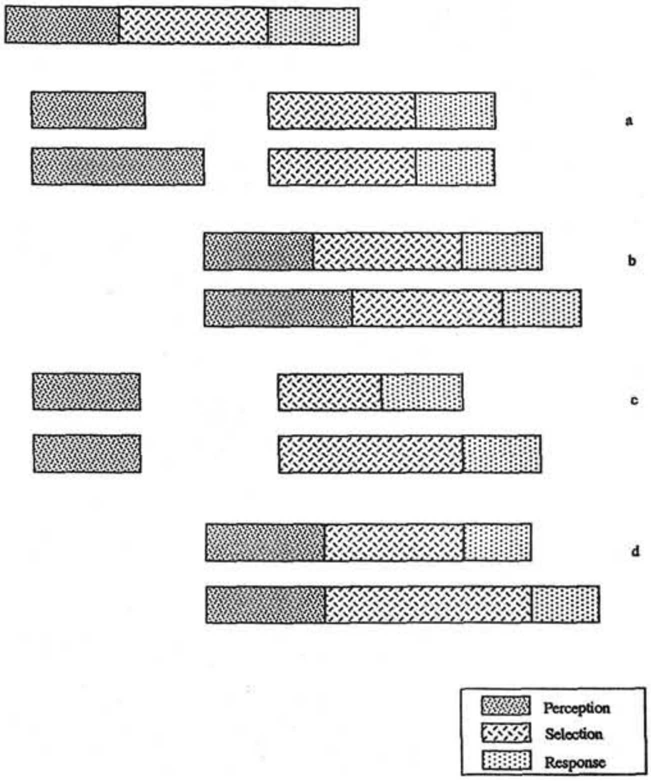

Figure 2. Schematic of psychological refractory period effects of manipulating different processing stages. Hypothetical stages of perception, selection, and responding are shown. Manipulation of perceptual processing produces underadditivity with stimulus onset asynchrony (SOA) because additional processing of Task 2 is absorbed by the time that Task 2 is at a bottleneck when SOA is short (a), but not when SOA is long (b). Additive effects on SOA are postulated to occur with processing manipulations that affect the bottleneck stage itself, occurring equally for both short (c) and long (d) SOA.

Although Figure 2 is based on the assumption of a response selection bottleneck, the basic logic holds independent of the exact operations associated with each processing stage. The key point to be emphasized here is that Experiment 2 provides a strong means for comparing the patterns of dual-task interference in normal participants and in a split-brain patient. We expected to replicate previous results with normal participants: Manipulation of the correspondence between stimuli and responses should be additive with SOA. If JW can independently prepare and select responses, then an underadditive interaction is predicted.

Method

Participants

The split-brain patient, JW, and the same four AM control participants were tested in Experiment 2. In addition, a new group of 13 CA control participants were recruited from the undergraduate participant pool at the University of California, Berkeley, and received course credit for their participation.

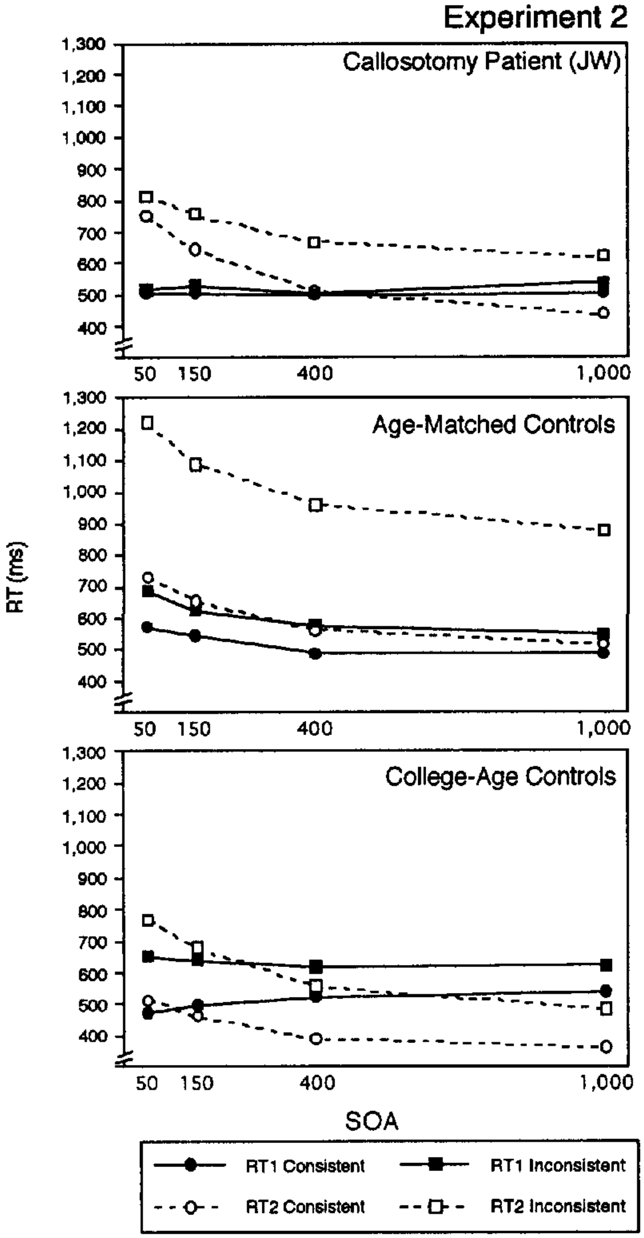

Figure 3. Response latencies for two spatial position tasks under consistent and inconsistent mapping conditions. Reaction time (RT) is plotted as a function of stimulus onset asynchrony (SOA) for the patient JW (top), age-matched controls (middle), and college-age controls (bottom). Solid lines represent Task 1, and dotted lines represent Task 2. Circles represent consistent mapping conditions, and squares represent inconsistent mapping conditions.

Stimuli and Procedure

Task 1 was identical to the spatial discrimination task used in the previous experiment. After a central fixation point was displayed for 800 ms, an empty circle appeared in the left visual field. The center of the circle was displaced laterally by 3.3° and was situated 2.4° above or below the horizontal meridian. A second empty circle was presented at comparable locations in the right visual field for Task 2. The onset times of the two circles were separated by SOAs of 50, 150, 400, and 1,000 ms.

Two response boards were used, one for each hand. Each board was oriented at a 45° angle, chosen to allow the participants a comfortable hand orientation while establishing a nonarbitrary correspondence between the stimuli and responses. For the left hand, the index finger was used to indicate that the circle was in the lower quadrant, and the middle finger was used to indicate that the circle was in the upper quadrant. This was assumed to be a compatible mapping in that the digit closest to the body is mapped to the lower target and the farther digit is mapped to the upper target (see Experiment 3). Compatible and incompatible mappings were used for the right hand in separate blocks of trials. On compatible blocks, the right index and middle fingers were mapped to the lower and upper targets, respectively. On incompatible blocks, the mapping was reversed. Given that Task 1 always involved a compatible mapping, the former condition creates a consistent mapping between the two tasks, and the latter condition creates an inconsistent mapping between the two tasks.[3]

As in Experiment 1, participants were instructed to respond as rapidly as possible on both tasks while attempting to minimize errors. Special emphasis was given to Task 1, the left visual field spatial discrimination task. Feedback was provided at the end of each block in the form of the number of errors on each task.

The split-brain patient and the AM control participants completed two test sessions. Within a session, these participants completed four test blocks, two of which involved consistent S-R mappings for the two tasks and two of which involved inconsistent mappings. Participants completed two blocks with one pairing followed by two blocks with the other pairing. On the first session, the consistent condition was tested prior to the inconsistent condition. This order was reversed for the second session. Each block consisted of 96 trials in which each position of the target for Tasks 1 and 2 occurred on half of the trials. Single-task blocks and a practice dual-task block were run prior to the dual-task test blocks to familiarize the participants with the tasks. Each session lasted approximately 2 hr.

The CA control participants were tested in a single session during which two test blocks of data were obtained for each condition (consistent and inconsistent). The order of conditions was counterbalanced across participants. Practice was only given under dual-task conditions.

Results and Discussion

The mean RTs are plotted in Figure 3. The percentages of trials in which either two responses were not made or were outside the RT criteria were 3.2% for JW, 2.8% for the AM controls, and 3.0% for the CA controls.

As in Experiment 1, a robust PRP effect was obtained for the split-brain patient and for the AM and the CA control participants. This effect held regardless of whether the S-R mapping for the two tasks was consistent or inconsistent. However, as described below, the PRP functions suggest that

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[3] It should be noted that our consistency manipulation differs in substantial ways from that used by McCann and Johnston (1992). In their study, the S-R compatibility manipulation was restricted to Task 2. In the current study, the consistency manipulation is between the two tasks, although as shown in Experiment 3, there is also a compatibility manipulation within Task 2.

the bottleneck for the patient may occur at a different stage than for the control participants. In addition, the response times on Task 1 for JW show a different pattern than those seen for the control participants. For the controls, RT1 is considerably slower when the tasks involved inconsistent mappings than when the mappings were consistent. For JW, this form of interference was greatly reduced.

The statistical analyses followed the same form as in Experiment 1. For JW, we used a series of repeated measures analyses for the three dependent variables (RT1, RT2, and errors). Group analyses were conducted on the AM and the CA controls, supplemented by individual analyses for the participants in the former group. In each analysis, there were three variables. The first was SOA. The second was between-task consistency (keeping in mind that the S-R mapping for Task 2 was always incompatible for the inconsistent condition). The third was the correspondence of the locations of the two targets on a given trial (same or different). Note that when the mappings were consistent, the responses involved homologous effectors on same location trials and different effectors on different location trials. When the mappings were inconsistent, homologous effectors were used on different location trials and nonhomologous responses were required on same location trials. Only trials in which both responses were correct were included in the analyses.

Task 2 Response Latencies

The effect of SOA was highly significant in all of the analyses: for JW and AM controls, *F*s(3, 9) = 108.27 and 15.06, respectively, *p*s < .001; for CA controls, *F*(3, 36) = 107.08, *p* < .0001. Thus, in accordance with Experiment 1 and the results of Pashler et al. (1994), the PRP effect persists after callosotomy. When the data were averaged over the consistent and inconsistent conditions, a decrease in RT2 of 256 ms from the shortest to the longest SOA was shown by the split-brain patient. This value falls between that obtained for the AM (296 ms) and the CA (218 ms) groups. However, as described below, the magnitude of the PRP effect interacted with consistency.

The effect of consistency was significant for JW, *F*(1, 3) = 13.70, *p* < .05, and for the CA controls, *F*(1, 12) = 129.88, *p* < .0001. This effect failed to reach significance for the AM controls, *F*(1, 3) = 5.85, *p* < .10, perhaps because of the between-subject design with a small sample size. In the more powerful individual analyses, this effect was significant for all four AM controls (all *p*s < .01). The RT2 data were considerably slower when the participants indicated *above* with the finger closer to the body and *below* with the finger farthest from the body than with the reverse mapping. The current design does not allow an unambiguous interpretation of this effect. It could reflect the effects of the compatibility manipulation restricted to Task 2, the inconsistency between the S-R mappings used for the two tasks, or a combination of these factors.

Nonetheless, consideration of the interaction between SOA and consistency reveals an important difference between the split-brain patient and the control participants. This interaction was not significant for the AM group: The additive effects of these two variables are in accord with the claim of McCann and Johnston (1992) that S-R compatibility affects a processing stage at or after the process producing the PRP effect. However, there was a significant interaction of SOA and mapping for one of the AM control's individual analyses and in the analysis of the CA participants, *F*(3, 36) = 24.91, *p* < .0001. In both of these cases, the increase in RT2 for the inconsistent mapping became smaller as SOA increased. For the CA participants, the difference between the inconsistent and the consistent conditions was 252 ms, 218 ms, 166 ms, and 122 ms across the four SOAs. This overadditivity likely reflects a carry-over effect from Task 1 to Task 2 related to the difficulty in maintaining conflicting S-R mappings. It seems plausible to suppose that when the two mappings are inconsistent, there is a cost associated with making the required reversal of the S-R mapping rule. Long SOAs would allow the participant to prepare for Task 2 in advance, thus reducing this cost and producing the overadditivity.

The interaction of SOA and consistency was also significant for the split-brain patient, *F*(3, 9) = 6.08, *p* < .05. However, here the interaction was one of underadditivity: For JW, the difference between the inconsistent and consistent conditions was 62 ms, 109 ms, 156 ms, and 185 ms across the four SOAs. Following the logic depicted in Figure 2, the underadditive interaction would suggest that the bottleneck for JW occurs at a later stage of processing than for the control participants. That is, unlike the controls, JW is able to begin response selection for Task 2, whether with compatible S-R mappings or with the more demanding incompatible mappings, during the bottleneck delay.

The third variable in this experiment was the correspondence of the target position for the first and second stimulus. The effects of this variable further suggest a differential pattern of interference for the split-brain patient and the control participants. For JW, response latencies when the two stimuli appeared at the same relative position (646 ms) were comparable to when they appeared at different relative positions (652 ms), *F*(1, 3) < 1.0. This main effect also failed to reach significance in either group analysis for the control participants.

However, the individual analyses for the AM controls revealed that for three of the participants, responses were significantly faster when the two stimuli appeared at the same rather than at different relative positions (differences of 184 ms, 55 ms, and 84 ms, all *p*s < .05). For the fourth AM control, this variable interacted with consistency, *F*(1, 3) = 19.93, *p* < .05. With the consistent mapping, this participant was faster by 33 ms when the two stimuli were at the same relative position; with the inconsistent mapping, responses were faster by 28 ms when the stimuli appeared at different relative positions. Thus, this participant showed a benefit when responding on keys at the same relative position (or involving homologous movements). For the other three participants, the benefit was related to the position of the stimuli. The important point is that the performance of the AM control participants showed a dependency between the specific stimuli chosen for a particular trial, a dependency that was absent in the split-brain patient.

Task 1 Response Latencies

When the S-R mappings for the two tasks were inconsistent, the control participants were much slower in performing Task 1, a finding which replicates those of Duncan (1979). The effect of consistency was significant for the AM controls, $F(1, 3) = 16.35, p < .05$, and the CA controls, $F(1, 12) = 45.41, p < .0001$. The RT1 was also slower for the split-brain patient when the S-R mappings were inconsistent, $F(1, 3) = 33.19, p < .05$.

However, the magnitude of this effect was substantially smaller than that observed for the control participants, suggestive of reduced interference following callosotomy between conflicting S-R mappings. For JW, the mean difference in RT1 between the inconsistent and the consistent conditions was 20 ms. For the AM and CA controls, the mean differences were 88 ms and 126 ms, respectively. Thus, the RTs on the primary task also suggest less interference for the split-brain patient compared with participants with an intact corpus callosum.

It should be noted that in the individual analyses, the effect of consistency was not significant for one of the AM controls. This might suggest that interference from inconsistent mappings is not obligatory in normal participants and that the reduced interference for JW reflected the use of a different strategy. An alternative explanation, however, is that the lack of an effect in this one control participant was due to an order effect. This participant began his first test session with the consistent mapping followed by the inconsistent mapping. Overall RTs improved over subsequent blocks, and his RT1s were actually faster by 40 ms with the inconsistent mapping. However, when tested with the reverse mappings on the second session, RT1 was slower by 92 ms with the inconsistent mappings when compared with the consistent mappings. JW followed the same protocol and also showed an improvement in terms of overall RTs. For him, the difference between the consistent and inconsistent mappings remained relatively constant (24 ms and 20 ms for the two sessions).

The effect of SOA was significant for the group of AM controls, $F(3, 9) = 6.70, p < .05$, and in all of their individual analyses. This provides additional evidence that their performance on Task 1 was not immune to the demands of the second task. Reaction times were slower at the shorter SOAs, a result in accord with the hypothesis that these participants did not segregate the two tasks as well as the split-brain patient did. Although there was a trend for this effect to be greater in the inconsistent condition, the analysis here was complicated by a marginally significant three-way interaction between SOA, consistency, and target correspondence, $F(3, 9) = 3.81, p < .06$. The effect of SOA was not significant for the CA controls, although this factor interacted with consistency, $F(3, 36) = 9.31, p < .001$. Mean latencies increased with SOA for the consistent condition and decreased with SOA for the inconsistent condition. The activation of consistent S-R mappings for the two tasks may be mutually facilitatory at short SOAs, whereas they may not be conflicting in the inconsistent condition (see De Jong, Liang, & Lauber, 1994).[4]

Errors

Elimination of the eccentric lexical decision task improved the overall accuracy of both the split-brain patient and the control participants. Overall, JW was correct on 96% of the trials when the tasks involved consistent mappings. His accuracy level dropped to 90% on the inconsistent blocks, $F(1, 3) = 33.8, p < .05$, with the majority of errors occurring on Task 2. The inconsistent blocks also increased the error rates for the CA controls (93% and 87% correct on consistent and inconsistent blocks, respectively), $F(1, 12) = 9.48, p < .01$, but not for the AM controls (93% vs. 90%).

A few of the other significant effects should also be noted. Both control groups tended to become more accurate with increasing SOA: for AM controls, $F(3, 9) = 4.84, p < .05$; for CA controls, $F(3, 36) = 26.7, p < .07$. Moreover, as was seen in the analysis of RT2, the AM controls were affected by the correspondence between the two targets. For three of these participants, the effect of target correspondence was reliable ($ps < .05$), with the mean error rate increasing by over 4% when the two targets appeared at different relative positions.

Individual Differences

Meyer et al. (1995) have argued that dual-task experiments, by their nature, require flexibility in terms of how participants coordinate the two tasks. They rejected a rigid processing architecture that postulates immutable bottlenecks. Instead, they proposed that participants adopt idiosyncratic strategies, so as to maximize efficiency through the coordination of flexible, executive control processes. To evaluate this hypothesis, they analyzed individual performance on PRP tasks in an effort to determine whether patterns observed in the group data also hold for individual profiles. For example, if the response selection hypothesis is correct, the additive effects between factors affecting response selection and SOA should not only be found across participants, but should also be observed at the individual level. Contrary to this prediction, Meyer et al. reported that the additive effects observed in some experiments are an epiphenomenon: the result of pooling participants who, as

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[4] We examined the overall data and some specific comparisons to see whether grouping tendencies might have influenced the main conclusions drawn in Experiment 2. For example, would grouping tendencies mitigate the differences in RT1 as a function of SOA or between the consistent and inconsistent mappings? To test these questions, we divided the participants in Experiment 2 into two groups based on their mean interresponse interval (IRI) at the shortest SOA (small IRI $M = 84$ ms; large IRI $M = 120$ ms). The groups did not differ in terms of the overall RT1 functions or in terms of the differences between RT1 on the consistent and inconsistent conditions (inconsistent RT1 − consistent RT1: small IRI group = 125 ms; large IRI group = 106 ms).

individuals, yield underadditive, additive, and overadditive functions.

This concern is especially relevant given our current reliance on a single case study to argue that the callosotomy operation produces qualitatively different sources of dual-task interference than those constraining the performance of the control participants. To further evaluate this claim, we assessed the degree of individual differences in the control participants. One primary interest here was to determine whether JW's performance was truly unique or whether it was mirrored by a subpopulation of the control participants. We focused on two measures, one based on the RT1 data and a second based on the RT2 data.

For the RT1 data, we calculated the difference between the consistent and the inconsistent conditions across all SOAs. For the RT2 data, a difference score was obtained to reflect the magnitude of the Consistency × SOA interaction. We subtracted the difference between the consistent and the inconsistent conditions at the shortest and longest SOAs and then took the difference between these two values (see Meyer et al., 1995, Figure 3). This value is negative when the variables are underadditive, reflecting the diverging functions, and positive when the variables are overadditive, reflecting the converging functions. With additive functions, of course, the value should be zero.

The results of these two analyses are shown in Figure 4. First, consider the results for RT1 (top). As noted previously, JW was 20 ms faster on Task 1 when Task 2 involved a consistent S-R mapping. Pairwise comparisons were made between each of the four blocks (e.g., Block 1 consistent vs. Block 1 inconsistent, etc.) and revealed that this difference was relatively constant, ranging from 13 ms to 29 ms. The

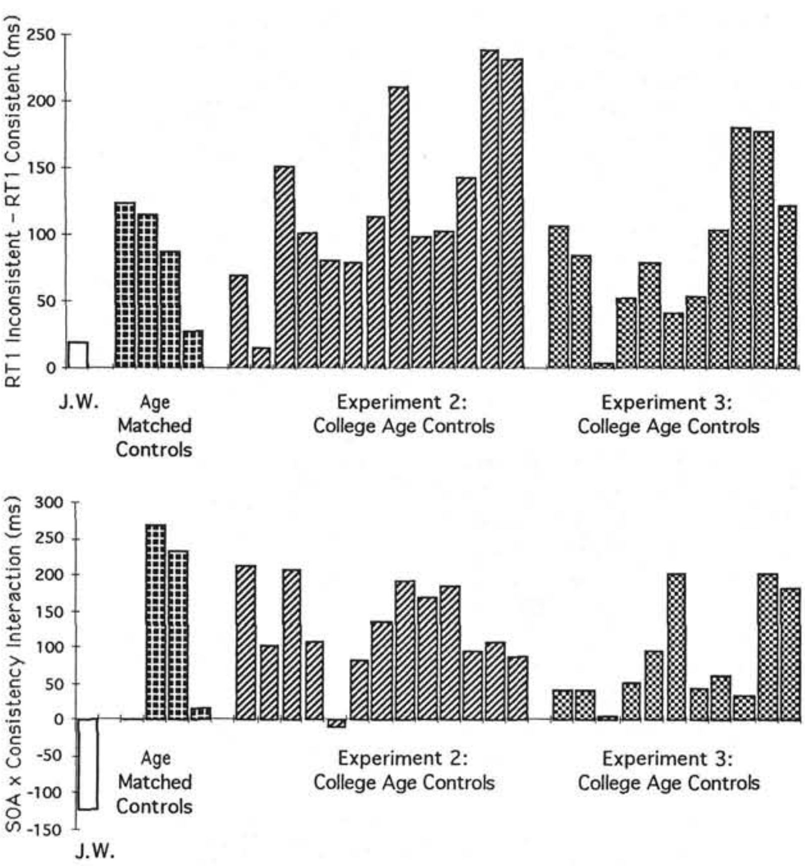

Figure 4. Top: Difference scores between Response Time 1 (RT1) in the inconsistent and consistent conditions for each individual in Experiments 2 and 3. For JW, the standard error calculated across the four blocks was 4 ms. For the age-matched (AM) controls (from left to right), the standard errors for the four blocks were 19 ms, 30 ms, 20 ms, and 44 ms. The mean for the 13 college-age (CA) controls in Experiment 2 was 126 ms ($SE = 19$ ms). The mean for the 11 CA controls in Experiment 3 was 91 ms ($SE = 17$ ms). Bottom: Difference scores to summarize the interaction between stimulus–response consistency and stimulus onset asynchrony (SOA) on RT2 for each individual in Experiments 2 and 3. The standard error across the four blocks for JW was 29 ms; for the four AM controls (from left to right), the standard errors were 53 ms, 50 ms, 57 ms, and 26 ms. The means for the CA controls in Experiments 2 and 3 were 129 ms ($SE = 63$ ms) and 87 ms ($SE = 73$ ms), respectively.

larger interference incurred by the control participants is indicated by the tendency of these participants to show a much larger difference between the two conditions.

JW's score is unlikely to reflect an extreme sample from a common distribution because his score is outside a confidence interval based on two standard error units for both the AM and CA controls. However, the uniqueness of JW's results can be questioned on the grounds that one of the CA controls had a smaller difference than JW (15 ms), and one of the AM controls had a difference that was similar to that observed with JW (27 ms). Alternatively, these low interference scores may, in part, be due to practice effects, because these two participants began training with the consistent condition. JW's low interference score was consistent across all four blocks, despite that in one session he was first tested on the consistent condition, and in the other session he was first tested on the inconsistent condition. There was no hint of an order effect with him, as evidenced by the extremely low standard error across the four blocks.

Although it remains possible that JW's interference score on RT1 is not unique, his data pattern on RT2 is far outside the entire range of performance of the normal participants. The difference scores based on RT2 are shown in the lower portion of Figure 4. The underadditivity observed with JW is reflected in his difference score of −122 ms. Pairwise comparisons were made between each of the four blocks completed by JW (e.g., Block 1 consistent vs. Block 1 inconsistent, etc.). For all four blocks, the difference score was negative and large in magnitude, ranging from −75 to −190 ms. In contrast, individual scores for the 17 control participants in this experiment ranged from −8 to 245. As reported previously in the group analyses, the AM participants produced an additive effect between consistency and SOA, and the CA participants produced an overadditive effect. These group effects are also apparent in the individual analyses; the difference scores for 16 of the 17 control participants were positive. For the one exception, the negative value was only −8 ms, and in neither block did the difference score extend to JW's range. Thus, there was essentially no overlap on this measure between the performance of JW and all of the control participants.

In sum, the individual analyses provide even stronger evidence that the PRP effect is arising at a different processing stage for the split-brain patient than for the control participants.

Summary

The results of Experiment 2 provide further evidence that the split-brain patient does not show identical patterns of dual-task interference as are found with control participants. Whereas a robust PRP effect was obtained for all of the participants, the split-brain patient showed minimal interference related to the consistency manipulation. We propose that this dissociation reflects the fact that, unlike normal participants, the split-brain patient is able to maintain independent S-R codes within each hemisphere. This hypothesis is supported by three findings. First, in general, on both RT2 and error measures, the AM controls' performance was influenced by the correspondence between the relative positions (or responses) of the two stimuli. JW's performance, however, was unaffected by this factor.

Second, JW showed a small increase in RT1 when the two tasks required inconsistent S-R mappings, whereas this manipulation led to approximately a 100-ms cost for the control participants (see also Duncan, 1979). The 20-ms cost for JW indicates that his performance on the first task was not impervious to the requirements of the second task. However, the lack of an effect of either target correspondence or SOA indicates that the cost here is rather generic. The S-R mapping for Task 2 in the inconsistent condition was likely more difficult because of the incompatible within-task mapping (as suggested by the large increase in RT2 for JW and the controls when the *above* response was mapped to the key closest to the body and the *below* response was mapped farthest from the body). This may have produced a generalized cost in performance, an effect that might be seen with any manipulation of Task 2 difficulty.

The third, and perhaps most intriguing, finding arose from the more detailed examination of the PRP functions. For this particular task, these analyses indicate that the bottleneck may arise at a later stage of processing for JW than for the control participants. For JW, the consistency manipulation proved to be underadditive with SOA. This result is consistent with the hypothesis that, for him, processing associated with mapping stimuli to responses occurs prior to the delay producing the PRP effect. That is, response selection for the two tasks can occur in parallel. The substantial underadditivity is in sharp contrast to the data for the control participants, for whom these two factors were either additive or overadditive. For this particular task, the results for the control participants are consistent with the hypothesis that they are unable to select the response for Task 2 until this operation is complete for Task 1.

Experiment 3

The first two experiments offered further documentation of response uncoupling in split-brain patients (Franz et al., 1996). In both studies, evidence of this uncoupling was based on the analysis of the participants' performance on Task 1. Task 1 was identical in all conditions: The participants indicated with a left-hand response the position of the stimulus. In Experiment 1, we observed that JW's responses on this task were not slower when the second task also required a manual response. Normal participants, in contrast, had a large cost on RT1 in the manual–manual condition compared with the manual–vocal condition. In Experiment 2, JW showed less interference than the control participants on Task 1 when the S-R mappings were inconsistent.

One concern with both of these findings is that they may simply reflect that JW had adopted a strategy that is more consistent with the experimental instructions. These instructions emphasized that participants should give priority to Task 1. Although we encouraged speeded responses on both tasks, the instructions explicitly stated that the response to the stimulus in the left visual field should be made first and without regard to the second stimulus. The fact that the control participants consistently showed an effect of SOA on RT1 and were affected by the response relations between the two tasks indicate that they failed to adhere to these instructions. Studies by De Jong and colleagues (De Jong, 1995; De Jong & Sweet, 1994) have demonstrated that performance on dual-task experiments can be strongly influenced by preparatory strategies. For example, even when the stimuli appear in an unexpected order, participants will generally respond in the anticipated order.

Although all of the participants, including JW, received the same instructions, JW may have been more compliant. Indeed, JW's willingness to participate in behavioral studies for over 15 years indicates that he is an exemplary research participant. This raises the possibility that the failure of the control participants to produce responses on the primary task in a relatively invariant fashion may be due to strategic factors.

To address this issue, we conducted Experiment 3 in order to provide control participants with strong motivation to follow our instructions regarding Task 1. The design was identical to that of Experiment 2 with one exception: The control participants were paid a bonus that was based on how quickly they responded to the first stimulus. It was expected that this would not only lower their overall RTs on Task 1 but would also flatten the SOA function. Of central interest was whether the monetary bonus would eliminate the cost on this task associated with the consistency manipulation.

By providing additional emphasis to Task 1, we also hoped to eliminate any tendency of the participants to group the two responses. As can be seen in Figure 3, the mean interresponse interval (IRI) at the shortest SOA for the CA control group is less than 100 ms in the consistent condition. Short IRIs can be indicative of a grouping strategy, and this might pose a problem in interpreting the data, especially if this tendency is more likely for one condition compared with another. Although the effects of consistency on RT1 did not appear to be related to mean IRI, we hoped to eliminate all grouping behavior by emphasizing Task 1.

Experiment 3 also provided a test of our assumption that the two S-R mappings for Task 2 provided different levels of compatibility. Prior to each pair of dual-task blocks, participants completed a practice and a test block in which they only responded with the right hand to the second stimulus. We expected that participants would be slower when the *above* and *below* responses were associated with the near (thumb) and the far (index finger) effectors. Although the compatibility issue is not critical in the current experiments, it seemed wise to perform this manipulation check.

Method

Participants

A new group of 12 CA control participants was recruited from the undergraduate and graduate student population at the University of California, Berkeley. These participants were paid a minimum of $5 per hr plus a bonus as described below. One participant was excluded from the final analysis because of excessively long latencies and errors.

Stimuli and Procedure

The stimuli and procedures were identical to those used for the CA controls in Experiment 2, with one exception. To motivate the participants to respond as quickly as possible on Task 1, we implemented the following monetary reward system. Each participant began the experiment with a practice block of 48 trials on Task 1 only. He or she then completed two test blocks of 96 trials on this task. Following the first test block, the mean RT was calculated and established a personal standard. The participant was informed that a bonus of $1 would be earned on a second test block if the mean RT was equal to or better than the standard. If the mean RT on the second block was slower than the standard, the bonus was reduced by $0.25 per 50 ms slower. To ensure accuracy, a $0.05 penalty was imposed for every error over five. Given this motivation, almost all of the participants were able to achieve the full bonus on the second test block. The mean RT from this block was then used as the standard for the four test dual-task blocks (2 consistent, 2 inconsistent).

The participants were tested in a single session. A practice block on each dual-task condition preceded a pair of test blocks. Participants were given a break between the two dual-task conditions. The order of testing (consistent followed by inconsistent or the reverse) was counterbalanced.

Results and Discussion

The mean RTs are presented in Figure 5. When these data are compared with those in Figure 3, it is clear that the monetary bonus was effective in reducing latencies on Task 1. Nonetheless, the monetary bonus stressing the first response failed to eliminate the consistency effect on RT1. Participants were consistently slower in making this response when the two mappings were inconsistent. The data

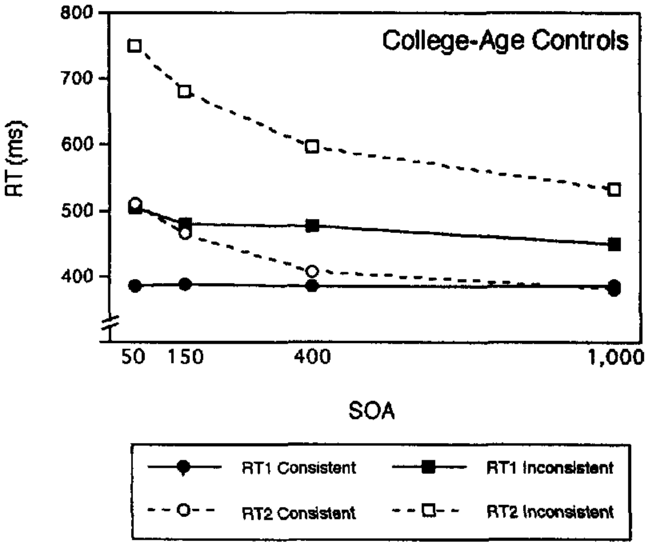

Figure 5. Response latencies for two spatial position tasks under consistent and inconsistent mapping conditions for control participants in Experiment 3. Solid lines represent Task 1, and dotted lines represent Task 2. Circles represent consistent mapping conditions, and squares represent inconsistent mapping conditions. RT = reaction time; SOA = stimulus onset asynchrony.

were analyzed in an identical format as that used in Experiment 2.

Task 2 Response Latencies

Significant effects were observed for SOA, $F(3, 30) = 69.36, p < .001$, and consistency, $F(1, 10) = 21.11, p < .01$. Moreover, there was a significant interaction of these variables, $F(3, 30) = 9.65, p < .001$. As observed with the CA controls in Experiment 2, this interaction was one of overadditivity. The difference between the inconsistent and consistent conditions was greatest at the shortest SOAs.

When the mean latencies for the shortest and longest SOAs are compared, the magnitude of the PRP effect was 139 ms for the consistent condition and 223 ms for the inconsistent condition. Although there are substantive methodological differences between Experiments 2 and 3, these values are slightly lower than those obtained for the CA group in the former experiment (156 ms and 280 ms), and the overall mean RTs are comparable across experiments.

Task 1 Response Latencies

The monetary bonus appeared to have its desired effect. The mean RTs on Task 1 were almost 150 ms faster in Experiment 3 than those obtained from the CA group in Experiment 2. Nonetheless, the effect of consistency persisted, $F(1, 10) = 30.89, p < .001$; mean RT1 was 91 ms faster on consistent blocks than on inconsistent blocks. Thus, much to our participants' dismay considering the manner in which their monetary bonus was calculated, substantial interference associated with maintaining inconsistent S-R mappings could not be avoided.

There was also a significant effect of SOA, $F(3, 30) = 4.81, p < .01$, and an interaction of this variable and consistency, $F(3, 30) = 5.27, p < .01$. The RT1 data were essentially flat for the consistent condition. However, for the inconsistent condition, RT1 decreased by 53 ms from the shortest to the longest SOA. We did not observe the inexplicable rise in RT1 for the consistent conditions that was obtained in Experiment 2 for the CA group.

Finally, note that the mean IRI at the shortest SOA rose to 185 ms in the consistent condition. As expected, the monetary incentive succeeded in reducing any tendency for the participants to group their responses.

Errors

Mean percent correct was 94% for the consistent conditions and 88% for the inconsistent conditions, $F(1, 10) = 23.28, p < .001$. Errors were also more likely for the shortest SOAs, $F(3, 30) = 6.69, p < .01$.

Single-Task Latencies

A mixed design was used to analyze the single-task blocks on the second task. The within-subject variables were SOA and S-R compatibility (reflecting the relationship of the stimuli to the response keys). The SOA had been varied in the same manner as in the dual-task blocks, but the first stimulus was not presented. The between-subject factor was order of testing (compatible before incompatible or vice versa), included to identify potential practice effects.

Overall, participants were faster by 40 ms when the *above* and *below* stimuli were mapped to the farthest and the nearest keys, respectively, compared with the reverse mapping, $F(1, 9) = 22.49, p < .01$. This suggests that this mapping does provide greater S-R compatibility.

However, this conclusion should be treated cautiously. It is also possible that the effect arises from residual interference from the mapping used for Task 1 on other blocks. This possibility is reinforced by the fact that there was a Compatibility × Group interaction, $F(1, 9) = 8.60, p < .05$. For participants who completed the compatible condition prior to the incompatible condition, the difference on single-task blocks was 69 ms. For participants with the reverse order, the effect was only 17 ms. These results suggest that the effects resulting from the manipulation of the S-R mapping for Task 2 reflect the consistency of the mappings between the two tasks rather than the compatibility within Task 2.

The single-task blocks can provide a rough assay of the dual-task cost for the first task. On the second test block with Task 1 alone, the mean RT was 309 ms. This is substantially lower than that obtained on the consistent (384 ms) and the inconsistent (475 ms) dual-task blocks. Note that the single-task blocks were always completed prior to the dual-task blocks. Any general practice effects should have favored the dual-task blocks.

Individual Differences

As in Experiment 2, we calculated individual difference scores to assess how well the group results were maintained at the individual level. These difference scores on RT1 and RT2 for the 11 participants in Experiment 3 are included in Figure 4. Despite the change in instructions and motivation, these measures of dual-task interference remained essentially unchanged. More important, these individual analyses further support the contention that JW's performance on these tasks is unique. The difference in RT1 between the inconsistent and the consistent conditions is twice that found for JW for 10 of the 11 participants. As in Experiment 2, the results for the one exception (difference score = 4 ms) may again be due to a practice effect, because this participant was first tested on the consistent condition.

Even more impressive, a positive difference score for the RT2 data was obtained for all of the participants, resulting in the finding of overadditivity of consistency and SOA in the group data. When pairwise comparisons were made between the two consistent and inconsistent blocks, none of the 22 comparisons fell within JW's range. In fact, only one such score was negative (−5 ms). Across Experiments 2 and 3, not one of the 28 participants with an intact corpus callosum showed any hint of underadditivity.

Summary

The results of this experiment argue against one version of a strategy-based explanation for the differences between the split-brain patient and normal participants. Control participants, even when given a strong incentive to respond as quickly as possible on Task 1, continued to show interference on this task when the two S-R mappings were inconsistent. The monetary incentive did produce a (between-experiment) reduction in mean RT and even succeeded in eliminating any changes in RT1 across the four SOAs for the consistent condition. However, there persisted a cost on RT1 of almost 100 ms when the two tasks used inconsistent mappings.

Thus, it is unlikely that the patient's lack of a response modality effect in Experiment 1 or of a substantial consistency effect in Experiment 2 is due to his giving greater priority to Task 1. Rather, the results across the three experiments indicate that the callosotomy operation has reduced at least one source of dual-task interference.

General Discussion

In the first two experiments, we observed a robust PRP effect in a split-brain patient, a finding that is in accord with the earlier report of Pashler et al. (1994). Although Pashler et al. used two lateralized versions of an identical visual motor task, our findings show that the PRP effect following callosotomy is evident when the two hemispheres are engaged in different tasks, and it occurs whether or not the tasks use the same output modality. The PRP effect persisted when a spatial discrimination task was paired with a lexical decision task, and the magnitude of the effect was statistically equivalent when the two responses were both manual, as when a manual response was paired with a vocal response.

Differences Between Normal Participants and Split-Brain Patient on PRP Tasks

A closer analysis of the patterns of performance suggests that the PRP effect following callosotomy may reflect different constraints than those that limit the performance of normal participants. The split-brain patient showed little—if any—evidence of response conflict between the two tasks. Three pieces of evidence support this conclusion. First, in Experiment 1, control participants showed an increase in (manual) RT1 when Task 2 also required a manual response; JW did not. Second, in Experiment 2, RTs on Task 2 were influenced by the correspondence between the two stimuli (or responses) for the AM control participants. The split-brain patient's performance was similar whether or not the two stimuli appeared in the same location or required the same response.

Third, in both Experiments 2 and 3, the control participants showed a large increase in RT1 when Task 2 required an S-R mapping inconsistent with that used for Task 1. This manipulation had a small effect on the response latencies for the split-brain patient, and this residual effect may reflect a generic cost associated with the added difficulty associated with requiring an incompatible S-R mapping for Task 2. Taken together, these findings demonstrate that the PRP effect for JW is relatively independent of conflicts in task demands. Although the Task 1 results may indicate that the patient was more compliant in following our instructions to give priority to this task, the results of Experiment 3 argue against this strategy-based interpretation. Even when highly motivated to focus on Task 1, the controls continued to show substantial interference on RT1 when using inconsistent S-R mappings for the two tasks.

Moreover, in the second experiment, there was a striking difference in the results for RT2 between the performance of the control participants and that of the split-brain patient. For the control participants the effects of consistency and SOA were either additive or overadditive. This pattern of results is consistent with the hypothesis that the bottleneck causing the PRP effect occurs prior to or at the same processing stage as that affected by the consistency manipulation (see McCann & Johnston, 1992; Pashler & Johnston, 1989). In contrast, for the split-brain patient, these factors were underadditive, consistent with the hypothesis that response selection for Task 2 can occur in parallel with response selection for Task 1.

In the current experiments, participants needed to maintain two sets of S-R mappings. Although the tasks were segregated by both the lateralization of the stimuli and the use of different effectors for the two responses, it appears that the normal participants were unable to keep the response codes distinct (Duncan, 1977, 1979). This may reflect a unity of working memory, a unity that is lost when the corpus callosum is severed. By this hypothesis, the manual–vocal condition of Experiment 1 would be easier than the manual–manual condition because the latter would require the participants to keep track of the task-to-hand assignments as well as the finger assignments within each task. Similarly, in the inconsistent condition of Experiments 2 and 3, different S-R mappings must be maintained in working memory. Researchers working in the area of S-R compatibility have argued that the process of generating an incompatible S-R mapping involves a generic, abstract transformation rather than a specific transformation whose effects can be restricted (De Jong et al., 1994; Hedge & Marsh, 1975).

The lack of response-competition sources of interference in these PRP studies meshes with the bimanual movement findings of Franz et al. (1996). As noted earlier, unlike normal participants, split-brain patients (including JW) were equally facile in simultaneously producing orthogonal trajectories as parallel trajectories. This spatial uncoupling indicates that the callosotomy operation allows S-R codes within each hemisphere to remain isolated from concurrent, and potentially incongruous, response preparation taking place in the other hemisphere. A similar uncoupling of response codes can account for why JW had little problem in using orthogonal S-R mappings for the two hands in Experiment 1 or conflicting mappings in Experiment 2. By inference, such coupling in normal participants can be attributed to cortical–cortical connections.

It is unclear whether such sources of interference are effector specific. Further research is required to address this issue. For example, if the second response of Task 2 were performed vocally, we might still expect to see a consistency effect on RT1. If the words "up" and "down" were substituted for the right-hand responses, it is possible that left-hand, manual responses on Task 1 would be disrupted if an incompatible mapping was used for Task 2. If this result were obtained, then a proper characterization of this source of interference would be in terms of abstract spatial codes (e.g., the abstract pairing of response labels with stimuli). Of course, this interference would only be expected in participants with an intact corpus callosum.

Implications of the PRP Effect Following Callosotomy

Pashler et al. (1994) concluded that dual-task performance in split-brain patients was limited in the same manner as in healthy participants. Specifically, they proposed that the callosotomy operation left intact a central response-selection mechanism that is sequentially accessed by the two tasks. Although JW does produce a PRP effect, his data deviate from the normal pattern in a number of substantive ways. Most notably, the underadditivity in Experiment 2 between S-R mapping and SOA challenge the hypothesis that JW's performance is limited by a structural bottleneck associated with response selection. Intuitively, the conclusion that JW is not constrained by a unitary response selection mechanism is more appealing than an alternative hypothesis linking such an operation to a subcortical locus. Moreover, it is in accord with the bimanual findings of Franz et al. (1996) showing that split-brain patients did not show signs of interference when planning incompatible spatial trajectories.

An alternative hypothesis is that for normal participants, there are (at least) two structural bottlenecks. De Jong (1993) postulated two bottlenecks that both contribute to the PRP effect: One bottleneck is associated with response selection, the second with response initiation. Within this framework, the current results suggest that the callosotomy operation selectively abolishes interference from the early, response selection bottleneck. As such, the persistent PRP effect for JW would be attributed solely to the residual effect of the late, response initiation bottleneck. This hypothesis provides a parsimonious account of our finding that consistency was underadditive with SOA for the split-brain patient. Because the effects of consistency are assumed to arise at a processing stage prior to response initiation, this effect should be mitigated at the shortest SOAs. Healthy individuals, however, still incur two bottlenecks and thus these two variables are additive (or overadditive if there is a carry-over effect from Task 1 to Task 2).

Meyer et al. (1995) have found that following training, healthy participants may produce underadditive functions in experiments using manipulations that presumably influence response selection. Perhaps the special training used in their experiments allows these participants to overcome the early bottleneck (and thus challenges its "immutable" status), rendering them more similar to the split-brain patient. However, even with this training, the late bottleneck remains evident.

Although De Jong's (1993) dual-bottleneck hypothesis provides a parsimonious account of the primary features of the data, one aspect of the current results is not in accord with his model. De Jong (1993) argued that the response initiation bottleneck was only operative when the two responses used a common effector system. In his second experiment, he found the effects attributed to a response initiation bottleneck to be essentially eliminated when one of the responses was made with the hand and the second with the foot. If this was the only bottleneck operating in the split-brain patient, we should have found the PRP effect to be absent or at least greatly reduced in the manual–vocal condition of Experiment 1. However, the results showed the PRP effect to be of comparable magnitude for the manual–manual and the manual–vocal conditions.

Meyer and Kieras (1997a, 1997b; see also Meyer et al., 1995) have introduced a computational model of dual-task performance that does not embody immutable central bottlenecks. According to their analysis, the dual-task interference can result from peripheral sources of interference associated with limitations in perceptual and motor processes. For example, two visual tasks can be more taxing than a combination involving one visual and one auditory task because the former requires that both stimuli draw on a common input modality. Similarly, their model presupposes a single manual motor processor. On this basis, one might expect greater interference when both tasks require manual responses compared with when one stimulus is responded to manually and the other vocally. Although the results from the normal participants in Experiment 1 are consistent with this hypothesis, the split-brain data question the hypothesis of a single manual processor.

In addition to these peripheral constraints, Meyer and Kieras (1997a, 1997b) argued that a potent source of "interference" arises because of the strategies participants adopt to comply with the experimental instructions (see also De Jong & Sweet, 1994; but see Ruthruff, Klaassen, & Pashler, 1996). In the present context, our instructions always emphasized that the response to Stimulus 1 should be made first. Except for the tendency of some control participants to group their responses, the participants were highly successful in meeting this task requirement. Most important, this fact holds for the split-brain patient: Indeed, we never observed a trial in which JW responded to the second stimulus prior to the first stimulus. This suggests that although the callosotomy operation eliminated some forms of response competition, the patient was still able to adopt a strategy that ensured that he obeyed the basic requirements of the experiments.

How might this be accomplished? An obvious answer is that the split-brain patient delayed his response to the second stimulus until after initiating his first response. Given his lack of transcallosal fibers, it is likely that the left hemisphere was dependent on subcortical or afferent projections for information about the current state of the responses to the first stimulus. The relatively large PRP effects for JW even in the most compatible situation—the consistent condition of Experiment 2—would suggest the use of indirect communication pathways.

These last comments point to some critical issues that need to be addressed in future research. First, what would happen if the two tasks were reversed so that the initial response was made with the right hand and the second response with the left hand? Numerous studies with split-brain patients have demonstrated that the left hemisphere is capable of monitoring responses dependent on right-hemisphere processing (reviewed in Gazzaniga, 1995). Evidence for the reverse-monitoring process is less compelling.

Second, would JW fail to show a PRP effect if instructed to respond to both stimuli as quickly as possible, without regard to order? The fact that the disconnected hemispheres are capable of independent perceptual analysis and response generation might lead one to expect that the PRP effect could be diminished. However, bimanual movement studies have shown that these patients are not capable of independently producing two movements: The movements remain coupled in the time domain (Franz et al., 1996; Tuller & Kelso, 1989).

A subcortical gating mechanism has been proposed to impose constraints on when responses can be implemented (Franz et al., 1996; Helmuth & Ivry, 1996; Ivry, 1997). This putative gate is similar in spirit to the late bottleneck proposed by De Jong (1993), with the exception that it applies to internal goal updating as well as to overt response initiation. Thus, whereas the present results argue against a unitary and immutable response selection bottleneck, it remains to be seen whether the coordination of concurrent tasks is fundamentally flexible. The persistent PRP effect following callosotomy may be attributed to a late structural bottleneck associated with response initiation/goal updating, strategies adopted to meet experimental instructions, or a combination of these factors.

In summary, we have shown that over a range of task manipulations, the PRP effect remains robust following callosotomy. Nonetheless, contrary to the conclusions of Pashler et al. (1994), the performance of a split-brain patient on such tasks is quite different from that observed with normal participants. Coupled with earlier findings (e.g., Kingstone & Gazzaniga, 1995; Luck et al., 1989), our findings demonstrate that the disconnected cerebral hemispheres can operate with remarkable independence, not only in terms of perceptual analysis but also in preparing responses.

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Received February 16, 1995
Revision received December 6, 1996
Accepted January 22, 1997 ■