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Dual-Task Interference and the Cerebral Hemispheres

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It has been argued that dual-task interference is reduced when the two cerebral hemispheres can carry out the two tasks independently. Evidence for this idea has arisen from studies involving manipulations such as lateralized stimulation or response, or requiring mental operations believed to depend primarily on a particular hemisphere. However, these studies have typically involved a very limited degree of response uncertainty, which appears critical in producing the most extreme dual-task interference (the *psychological refractory effect*). Pairs of tasks with independent response uncertainty were examined, and various manipulations were used to promote hemispheric task separation. Dual-task interference was not modulated by these manipulations. It seems likely that response selection represents a central bottleneck, in the sense that this process cannot operate simultaneously and independently in the two hemispheres.

When two tasks are performed close together in time, response delays are typically observed (Welford, 1952). In the case of simple tasks, these delays appear to be caused by a bottleneck in the response-selection stage of processing: When the response is being selected for one task, response selection in the other task must be postponed (McCann & Johnston, 1992; Pashler, 1984; Pashler & Johnston, 1989; Welford, 1952). Some additional mental operations also appear to require the same bottleneck mechanism (Pashler, in press; Pashler & Christian, 1992). The clearest evidence for the bottleneck comes from the simplest dual-task situation, namely the psychological refractory period (PRP) paradigm (Welford, 1952). Here, the subject is presented with two stimuli (S1 and S2) in rapid succession, separated by a stimulus onset asynchrony (SOA), and required to make a response to each stimulus as quickly as possible (R1 and R2, respectively). Under these conditions an increase in the latency of the second response (RT2) is almost invariably observed, a slowing that increases as the SOA between the two stimuli is reduced (the *PRP effect*). This slowing arises even when very simple tasks are used, such as two-alternative choice tasks with simple stimuli and manual or vocal responses. The latency of the first response (RT1) may or may not be affected (Pashler & Johnston, 1989).

In a somewhat different tradition, and with rather different experimental methods, various researchers have examined the interaction between the left and right cerebral hemispheres in dual-task performance. Some researchers have suggested that each cerebral hemisphere controls its own independent resources (e.g., Friedman & Polson, 1981) and that the efficiency of dual-task performance depends heavily on whether the same or different hemispheres are used by the two tasks, with less interference arising in the latter case (e.g., Kinsbourne, 1981).

These two approaches may be termed the *PRP approach* and the *cerebral hemispheres approach* to dual-task interference, respectively. The two approaches have been pursued in almost complete isolation: Discussions and studies of the PRP effect have not considered hemispheric issues, whereas most discussions of possible hemisphere-specific resources have not explicitly acknowledged evidence for a central response-selection bottleneck (but see Kinsbourne, 1981), nor have they focused on tasks likely to manifest this bottleneck. Consequently, the conclusions reached with these two very different approaches to dual-task interference remain to be reconciled. The present article reports five studies that examine hemispheric factors in dual-task interference, and in the General Discussion section we attempt a partial reconciliation of the PRP approach and the cerebral hemispheres approach. We begin by (very briefly) reviewing some important findings from each approach.

The Central Bottleneck

As noted above, recent studies of the PRP effect appear to confirm Welford's original suggestion that the selection of actions in a pair of choice response time (RT) tasks involves a bottleneck that necessitates delays in one or both tasks (see Pashler, in press, for a summary). Evidence for this view comes from several sources. First, chronometric studies that have manipulated the duration of different stages of the second task in the PRP paradigm have confirmed specific patterns of interaction predicted by a response-selection bottleneck and provided evidence against alternative bottleneck models (Carrier & Pashler, 1992; Fagot & Pashler, 1992; McCann & Johnston, 1992; Pashler, 1984; Pashler &

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Johnston, 1989). Second, analysis of the dependencies between the two RTs in PRP experiments favors a bottleneck model (Pashler, 1989, 1990). Third, recent dual-task studies have required a speeded response to one task, while recording accuracy on another task that involves a brief masked stimulus. The results show that even quite demanding perceptual processes (e.g., conjunction search) in the second task can proceed with very little interference from a concurrent task (Pashler, 1989). Fourth, recent results show that despite earlier reports to the contrary, typical PRP functions can be obtained with tasks that use very different sorts of responses, such as a vocal and a manual response (Pashler, 1990) or a manual response combined with a saccadic eye movement (Pashler, Carrier, & Hoffman, in press).

These various sources of evidence strongly suggest that although some portions of two tasks in a PRP situation will typically overlap temporally, certain critical stage(s) cannot overlap, thus constituting a bottleneck. Furthermore, the bottleneck is cognitive rather than simply motoric. For this reason, it may be described as a "central" bottleneck, using this term in a functional rather than anatomical sense.

This converging evidence for a central bottleneck does not, however, provide any information about the interaction of the two cerebral hemispheres in dual-task performance. Indeed, in the studies mentioned (and in the other PRP experiments with which we are familiar) no attempt has been made to use tasks that depend specifically on one hemisphere rather than another. Most studies have included visual stimuli that span the visual midline, and therefore project to both hemispheres. Studies using manual responses have typically involved both right-hand and left-hand responses (varying from trial to trial), and the effects of this variable have not been reported. Therefore, it is possible that strong effects of same- versus different-hemisphere performance may have been overlooked in PRP studies, and that evidence for a central bottleneck often arose because both tasks often depended on the same hemisphere.

Studies of Hemispheric Involvement in Dual-Task Interference

A vast neurological and psychological literature demonstrates at least some degree of functional specialization of the cerebral hemispheres in sensorimotor and cognitive performance. The clearest case is the left-hemisphere specialization for language, found in most individuals (Broca, 1865; Wada & Rasmussen, 1960). More controversially, it is often said that the left hemisphere is specialized for "analytic" cognitive processes, whereas the right hemisphere is specialized for nonverbal or "holistic" information processing (see Springer & Deutsch, 1985, for a review). In addition, it is not disputed that each hemisphere receives predominantly contralateral sensory input and directly controls musculature on the contralateral side of the body.

What are the implications of hemispheric specialization for people's ability to perform two tasks at the same time? The most extreme proposal that would link hemispheric specialization with dual-task interference in normal human beings was advanced by Friedman and Polson (1981). They suggested a "multiple resources" model, according to which "the left and right hemispheres together form a system of two mutually inaccessible and finite pools of resources" (Friedman & Polson, 1981, p. 1031). Therefore, if a person attempts to perform two tasks simultaneously, and each task requires resources from a separate hemisphere, relatively little interference between the tasks is to be expected. (Friedman and colleagues have also tested predictions about the effects of varying task emphasis, but these analyses are not directly relevant here.) A related model is the "functional distance" theory of Kinsbourne and colleagues (Kinsbourne, 1981; Kinsbourne & Hicks, 1978), which states that two tasks are most efficiently processed in brain areas that are "functionally distant," with the two hemispheres being merely one case of relatively distant structures.

Various studies have manipulated the nature of the task, the visual field of stimulus presentation, and the musculature required in response in order to create pairs of tasks likely to be carried out by the same or different hemispheres. The two formulations mentioned above predict that considerable interference should occur when both tasks require resources from the same hemisphere, but there should be much less interference when different hemispheres are involved. Numerous findings supporting this general prediction have been reported (Friedman & Polson, 1981; Friedman, Polson, & Dafoe, 1988; Friedman, Polson, Dafoe, & Gaskill, 1982; Kinsbourne & Hicks, 1978).

One example is an experiment by Friedman et al. (1988). The two tasks involved were speeded finger-tapping, and reading and remembering nonsense words. Subjects in the dual-task situation remembered more from the verbal task when they tapped concurrently with their left hand than when they tapped with their right hand. Similarly, Hiscock (1982) found that right-handed tapping suffered more interference from concurrent recitation of tongue-twisters than did left-handed tapping. Other studies have confirmed this pattern using a variety of verbal tasks (Kee, Hellige, & Bathurst, 1983; Kee, Morris, Bathurst, & Hellige, 1986).

A study reported by Liederman (1986) used lateralized presentation to influence which hemispheres carried out arithmetic tasks. Subjects were given three briefly exposed numbers on the computer screen. These numbers were arranged such that the digit at fixation was to be added to a top number and subtracted from a bottom number; in the second experiment, the numbers were reversed so that the subtraction task was above the addition task. The addition and subtraction problems could be presented to the same hemifield or different hemifields. The results showed that a higher proportion of problems were solved correctly when the addition problem was directed to one hemifield and the subtraction problem to the other hemifield, compared to the same hemifield condition. The interpretation was that in this case the two different tasks were carried out by the two different hemispheres.

Other investigators have varied the hemifield to which visual stimuli are presented and observed interactions with a concurrent task. For example, Hellige, Cox, and Litvac (1979) examined the effects of a verbal memory load on processing of brief lateralized displays and concluded that "the left hemisphere functions as a typical limited-capacity information processing system that can be influenced somewhat separately from the right hemisphere system" (p. 251). To mention still another oft-cited example, Kinsbourne and Cook (1971) used lateralized motor responses, examining the effect of balancing a dowel on either the right or left index finger and speaking. The results also showed greater interference with two tasks thought to require resources from the same hemisphere: Balancing times were longer in the verbal condition when the left hand was used than when the right hand was used.

Methodological Differences

One important difference between the dual-task paradigm used by studies addressing hemispheric issues, on the one hand, and the dual-task studies using the PRP method that were described earlier, on the other, is that in the PRP paradigm, subjects must select a separate choice response to each of two nearly concurrent stimuli. By contrast, virtually all of the tasks used in the investigations of hemispheric factors may—for different reasons in different cases—have omitted any requirement for response selection (which appears to lie at the heart of the processing bottleneck). None of these researchers suggested that their proposals were meant to exclude response selection or any other information processing stages, nor did they discuss evidence for postponement as revealed by the PRP effect. Therefore, it appears that the omission of the requirement for two response selections in these tasks was purely a matter of chance, perhaps reflecting the relative isolation of the "PRP tradition" and the "hemispheric tradition" that was noted above.

But whatever the reason, it does appear that dual response selections were probably not involved in the great majority of these studies. Repetitive finger tapping, used in several of these studies, does not seem to call on the bottleneck mechanism for selection of each individual finger movement. Evidence on this point comes from Pashler and Christian (1992), who had subjects tap as fast as they could; at some point during the tapping a tone was sounded, requiring a speeded vocal response. No significant interference was found in either task (compared with single-task controls), nor was any interdependency between the latencies of the tapping and vocal responses detected. However, when response selection was reintroduced by requiring subjects to tap once or three times, depending on a visual stimulus, the tone response was greatly delayed at short SOAs. showing the typical PRP effect of hundreds of milliseconds, and interresponse latency dependencies were also dramatic.

Indeed, the effects of verbal tasks on tapping speed in the hemispheric studies cited above are typically quite small. For example, Kee et al. (1983) found that concurrent verbal tasks produced decreases in tapping speed on the order of 2%-6%, and Friedman et al. (1988) observed effects mostly under 10%. In terms of absolute slowing of the intertap interval, these effects are mostly well under 50 ms.

Balancing a dowel (Kinsbourne & Cook, 1971) undoubtedly requires visually guided corrective responses, but it is impossible to know how frequently these occur or when they are occurring. Reading words (Hellige et al. 1979) may be the sort of perceptual operation that does not involve the central bottleneck at all (Pashler, 1989), whereas encoding information into long-term memory may or may not place demands on central bottleneck mechanisms (appropriate investigations do not seem to have been carried out).

Finally, many of these studies have required subjects to hold onto a verbal memory load over the period of time that another task is being performed. Though this is, in a sense, a dual-task experiment, holding the memory load may not require any active mental operations during the retention interval (see Pashler, 1984). Consistent with this is the fact that holding a memory load induces very small delays in a concurrent choice RT task, compared with a typical PRP effect. For example, Logan (1978) performed a series of experiments in which seven-digit memory loads were superimposed on various RT tasks; effects were on the order of 50 ms, whereas PRP effects generally amount to several hundred ms of slowing at the very least (the data reported below will provide numerous examples).

The study of Liederman (1986) seems to require subjects to use multiple sources of information to select a single response. It is not clear whether this would invoke the same bottleneck limitation as selecting two independent responses (Fagot & Pashler, 1992). But in any case, Lieder-man's effects might have nothing to do with hemifield of presentation per se. For example, her bilateral displays—which produced superior performance—may have presented a geometric configuration of stimuli more conducive to subjects' familiar left-to-right scanning patterns.

In summary, then, it is noteworthy that studies demonstrating hemispheric effects on dual-task interference have generally relied on tasks that produce milder forms of dual-task interference than that observed in the PRP situation. Because response uncertainty has been omitted in the hemispheric studies, the role of hemispheric factors in the more pronounced interference associated with response selection remains to be clarified.

Nonetheless, in each of the cases discussed, there was dual-task interference. So far, nothing has been said of its source. The existence of relatively mild interference effects not attributable to direct competition for the bottleneck mechanism is actually consistent with a response-selection bottleneck model. Holding a memory load, for example, may interfere primarily with preparation for carrying out a speeded task (Logan, 1978; Pashler, 1984). When the task is carried out, response selection may proceed more slowly than normal because refreshing and retaining the memory load in advance of the trial prevented the stimulus-response association that guides response selection from being readied to maximum strength. Then, response selection may be slowed because of what failed to happen prior to the trial, not because concurrent activity actually caused it to be delayed (as with two independent tasks). (This account was proposed by Logan, 1978). The source of the very mild effects of concurrent tapping are unknown, although they too might reflect preparation rather than delay effects (this issue will be discussed further in the General Discussion section). Interference in perceptual judgments may reflect competition for modality-specific resources (Pashler, 1989) as well as preparatory factors.

Before turning to the present work, one final study must be mentioned that did examine hemispheric interaction in the PRP paradigm. Dimond (1970) presented either one or two arrows, each pointing either left or right to signal a left-hand or right-hand response. Signals were separately directed to either hemifield of each eye. Dimond reported that the refractory effect was greatly amplified when the signals were directed to the same hemisphere, from which he concluded that refractoriness was at least partly attributable to competition for hemispheric resources. One difficulty with this study is that as soon as the subject could detect that two signals were presented, response uncertainty was eliminated: He or she should respond with both hands. Selection of a pair of responses as a couplet does not show evidence of the bottleneck (Fagot & Pashler, 1992). So the situation appears to differ quite drastically from a PRP task with two tasks each involving its own independent response uncertainty. Another difficulty was that when two stimuli were presented to the same hemisphere, they were also presented to the same part of the visual field, optimal conditions for producing binocular rivalry. Dimond was aware of this problem and presented a control experiment finding no evidence of rivalry per se, but the conditions in the control experiment were somewhat different. In view of these difficulties with the Dimond experiment, a reexamination of the issue seemed appropriate, using methods that involve genuinely independent tasks with response uncertainty and no possibility of binocular interactions.

The Present Approach

In summary, various investigators have demonstrated clearly that dual-task interference in certain tasks can be modulated by hemispheric variables; however, the tasks they have investigated do not seem to generate full-scale interference of the sort associated with the central bottleneck. Rather, they generate other, less dramatic forms of interference that may have heterogeneous causes.

Given these unresolved issues, a particularly crucial open question is whether interference of the bottleneck variety can or cannot be averted by designing two tasks so that they are carried out by separate hemispheres. In the experiments that followed, we used a PRP paradigm with various tasks designed to rely principally on one hemisphere or the other. In keeping with the PRP paradigm, two independent response selections were required. To encourage same- versus different-hemispheric performance of the tasks, we used the same lateralized input, lateralized output, and processing code manipulations used by Friedman, Kinsbourne, Lieder-man, Hellige, and their colleagues (and others suggested by the literature on hemispheric specialization, as noted below).

Two very different hypotheses can be entertained. The proposals of Dimond, of Friedman and her colleagues, and of Kinsbourne have suggested that dual-task interference is attributed to hemispheric resources or cortical distance related interference. Although these researchers did not specifically refer to response selection, they said nothing to suggest any exclusion of this processing stage. Therefore, the hemispheric resource account leads one to expect little or no interference between the two tasks so long as one hemisphere is used for the first task and the other hemisphere is used for the second task. Kinsbourne's formulation would predict, at the very least, substantially less interference in this case compared with the same-hemisphere case. The alternative hypothesis, of course, is that interference will not depend on whether the same or different hemispheres are used for each task. This would support the central bottleneck model and broaden the sense in which the bottleneck can be termed "central."

Assumptions About Lateralization

The studies reported below will use the same, by now standard, manipulations to lateralize tasks that have been used by researchers advocating hemisphere-specific resources or interference. The difference is that our tasks include response uncertainty. It should be noted that these experiments are not based on an assumption that the standard hemispheric manipulations actually succeed in producing completely lateralized task performance. The point is rather that it has been widely claimed that these manipulations suffice to determine which hemispheres carry out tasks, and thereby to modulate dual-task interference. If it should turn out that the interference associated with response uncertainty is not so modulated, then the methodological assumptions of Friedman and the other researchers regarding task lateralization, as well as the hemispheric interference models, might need to be reexamined and possibly changed or restricted.

A Note About Capacity Sharing

One final point about methodology is worth noting. The investigations of hemispheric factors described above have tended to assume a model according to which dual-task interference is attributable to graded sharing of mental resources or capacity between tasks. The idea of graded sharing has often been assumed rather than argued for with evidence. Kahneman (1973) and McLeod (1977) specifically applied it to the PRP situation, but its predictions for that situation have not thus far been supported empirically (Fagot & Pashler, 1992; Pashler, 1984, in press). Rather, evidence has tended to favor discrete postponement of the critical processing stage(s). There are a number of interesting capacity-sharing possibilities that are also addressed with the same- versus different-hemisphere comparison in the PRP design. For example, it is possible that discrete postponement of processing stages might be a within-hemisphere phenomenon, whereas between-hemisphere task combinations might suffer only the graded interference predicted when two tasks draw on a common resource pool (see Fagot & Pashler, 1992, for a discussion). The experiments reported below should either validate or discredit such possibilities.

Experiment 1

The first task in this experiment required a verbal response to the pitch of a tone (subjects said "high" or "low"). Although the (binaural) auditory stimulus is projected to both hemispheres, vocal response selection and production is controlled by the left hemisphere in the great majority of subjects (Broca, 1865; Sperry, 1974). The second task required the subject to make a manual keypress response to the position of a disk on a computer screen. When the stimulus was in the left visual field (LVF), a left-hand response was required, and when the stimulus was in the right visual field (RVF), a right-hand response was required (within each hemifield, the stimulus could be above or below the horizontal midline, determining whether the upper or lower of two response keys on the appropriate side should be pressed; thus, the task was a four-choice task). Given the lateralized input and output, this task is presumed to depend basically on the hemisphere contralateral to the stimulus (Springer & Deutsch, 1985).

Thus, this design involved a first task presumed to depend heavily on the left hemisphere, and a second task that allowed a within-subjects mixed-trials comparison of a concurrent processing with the left hemisphere versus the right hemisphere.

Method

Subjects

Thirteen right-handed undergraduates at the University of California, San Diego, participated as subjects in the experiment either for partial fulfillment of a course requirement or in return for payment. Data were used from 12, of whom 6 were women. The Edinburgh inventory was issued to each subject to determine handedness (Oldfield, 1971).

Apparatus and Stimuli

The stimuli were presented on NEC Multisync 2 or 2a monitors, controlled by IBM PC microcomputers (equipped with a Paradise VGAPlus graphics card, providing a display resolution of 640 X 200 pixels). The screen was divided into four quadrants by two lines, one vertical and the other horizontal. The vertical line extended the entire height of the screen (8 cm from the fixation point to the edge of the screen—7.6° based on a typical viewing distance of 60 cm) and the horizontal line extended the entire width of the screen (12 cm—11.3°—from the fixation point to the edge of the screen). These lines intersected at the center of the screen, and this intersection served as the fixation point. The lines were white at the center of the screen (extending 1.8 cm vertically and 1.8 cm horizontally) and were red elsewhere, to highlight the fixation point. The visual stimulus (S2) was a white disk that appeared in one of four quadrants. The center of each disk was approximately 4.7 cm (4.5°) from the red vertical line and 6.6 cm (6.3°) from the horizontal red line. The disks measured about 2.6 cm in diameter (2.4°). Tones (S1) were presented at either 900 Hz or 300 Hz. Subjects' vocal responses to the tones were detected with a directionally sensitive microphone and relayed to a Gerbrands Corporation voice activated relay, which input a signal into the computer.

Design

The experiment was divided into 12 blocks of 32 trials each. The present experiment used a 4 X 2 X 2 factorial design. The factors were SOA between tone and disk (50, 150, 500 and 1,000 ms), whether the disk appeared in the LVF or the RVF in the second task (left-right), and whether the disk appeared in the upper or lower quadrant of the screen in the second task (up-down). The pitch of the tone was determined randomly and independently on each trial. The conditions were presented to the subjects in random order, with two trials in each condition per block.

Procedure

Subjects were given written instructions describing the tasks. The instructions stressed the importance of responding to each stimulus as quickly and as accurately as possible, and grouping of the two responses was discouraged. Prior to the collection of data, subjects completed one practice block containing 32 trials.

Each trial began with the presentation of the cross as a warning signal and fixation point. It remained present for one second. The first stimulus (S1) was either the high or low tone; this was presented for 150 ms. After an SOA of 50, 150, 500, or 1,000 ms, the disk (S2) appeared in one of four quadrants on the screen. The disk (S2) remained for 150 ms. The subject responded to S1 by saying the word "high" or "low" for a high- or low-pitched tone. When the disk (S2) was in the upper left, lower left, upper right, or lower right quadrant, subjects were instructed to respond by pressing the [a], [z], ['], or [/] key on the keyboard, using their left middle, left index, right middle, or right index finger, respectively. Thus, the position of the response keys was quite compatible with the position of the visual stimulus on the screen.

If an error was made in the second task, the word "ERROR" appeared in green in the center lower half of the screen with a duration of 500 ms. If no response was made by 2.1 s after S2 was presented, the trial was aborted. The intertrial interval between completion of responses on a given trial and onset of the fixation point for the next trial was 1.5 s. At the end of each block the subject rested and was provided with feedback. This feedback consisted of percentage correct and average RT for both the vocal response and the keypress response for that block and each of the preceding blocks.

Results

Response times of less than 150 ms or greater than 2,000 ms were discarded as outliers. The data for 1 subject was discarded because this subject's vocal responses were rarely picked up by the voice key. This left 12 (7 women). Table 1 presents mean correct RTs and error rates as a function of all independent variables, and Figure 1 shows RT1 and RT2 as a function of task and SOA.

Basic RT Effects

First, an analysis of variance was performed on the vocal RT1 RTs. The vocal RT1 was not significantly affected by SOA ($F < 1$). However, RT1 was slightly faster for when the disk was on the right (525 ms) than the left (531 ms), $F(1, 11) = 6.8, p < .05$.

Second, an analysis of variance was performed on manual RT2 response times including the same factors. SOA af-

Table 1
Error Rates and Response Times (RTs, in Milliseconds [ms]) for Left and Right Responses: Experiment 1

	Stimulus onset asynchrony							
	50 ms		150 ms		500 ms		1,000 ms	
Response	RT	Error	RT	Error	RT	Error	RT	Error
Left								
R1	521	—	535	—	528	—	539	—
R2	590	.007	541	.009	429	.028	382	.021
Right								
R1	527	—	519	—	527	—	528	—
R2	590	.019	521	.014	423	.028	367	.030

fected RT2 significantly, $F(3, 33) = 18.4, p < .001$, reflecting a dramatic increase in RT2 as SOA is shortened (the PRP effect). RT2 was also slightly faster when the disk was above the midline (475 ms) rather than below (485), and the effect of this factor (up-down) was significant, $F(1,11) = 6.3, p < .05$. RT2 was slower when the disk was in the LVF (485 ms) than in the RVF (475 ms); this factor (left-right) was also significant, $F(1,11) = 6.0, p < .05$. The interaction of left-right by up-down was significant, reflecting faster responding to disks in the upper right, $F(1,11) = 5.4, p < .05$. The following interactions were nonsignificant: Up-Down X SOA, $F(3, 33) = 2.4, p > 0.07$; Left-Right X SOA, $F(3, 33) = 1.12, p > .35$; Up-Down X Left-Right X SOA, $F(3, 33) < 1$.

The slope of the function relating RT2 to SOA decreased as SOA was reduced, and over the range from SOA 50 to SOA 150 it was -.59. This figure falls somewhat short of the -1 slope that is frequently observed in PRP tasks at short SOAs.

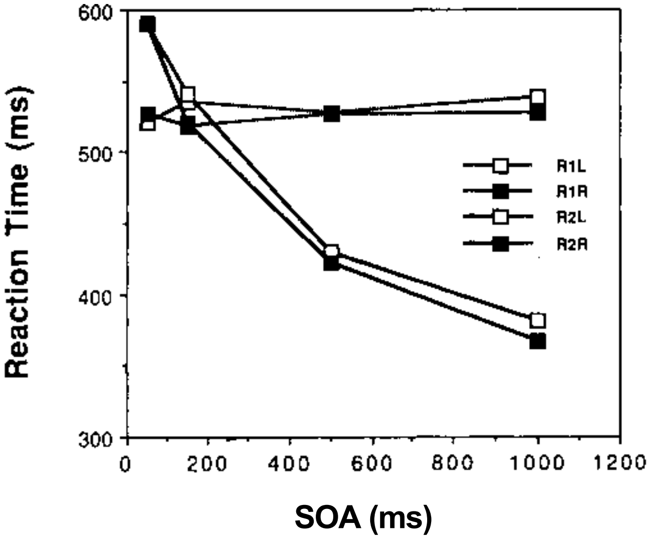

Figure 1. Experiment 1. Mean response time for R1 and R2 as a function of stimulus onset asynchrony (SOA) and response type. (R1 or R2 means first or second response latency; L or R refers to whether R2 is left- or right-hand response.)

Relationship Between R1 Speed and R2 Speed

Figure 2 shows the relationship between the speed of the second response and the speed of the corresponding first response. This figure was plotted by collecting the RT1s for each Subject X SOA X Left-Right position, rank ordering them and dividing them into quintiles. The mean of the corresponding RT2s was then computed. For any point on the graph, the value on the y axis represents the speed of RT2s on trials where RT1 lay within a given quintile, averaged across subjects, and the value on the x axis represents the mean speed of the RT1s within this quintile. Overall, the slower the first response, the slower the second response. As SOA was reduced, the dependency of RT2 on RT1 became stronger. This was verified by an analysis of variance with RT2 as dependent variable, which included as factors the independent variables mentioned earlier plus RT1 quintile (with Levels 1, 2, 3, 4, 5): RT1 quintile interacted with SOA, $F(12, 132) = 9.2, p < .001$. The interaction of RT1 quintile and left-right was nonsignificant, however, $F(4, 44) < 1$.

Errors

There were more R2 errors when the disk was above fixation (.013) rather than below (.026), $F(1, 11) = 6.3, p < .05$. There were no other significant effects involving errors. (Vocal errors were not recorded.)

Discussion

The latencies show the most common pattern found in PRP experiments: SOA had no significant effect on RT1, but it had a dramatic effect on RT2. This is to be expected if the first task is completed as fast as possible without interference from the second task, whereas critical stages of the first task must be completed before processing of the second task may begin.

The slope relating RT2 to SOA over the range 50-ms SOA to 150-ms SOA (see Figure 1) was -.59, which falls short of the -1 slope that is sometimes found in PRP experiments; this deserves comment. This might be attributable to the relatively fast vocal first task. If critical stages in the first task are completed quickly, the first task would often be

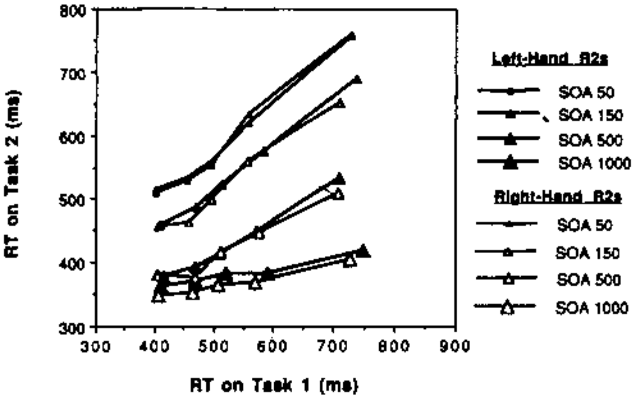

Figure 2. Experiment 1. RT2 as a function of RT1 (broken into quintiles) as a function of stimulus onset asynchrony (SOA) and right versus left R2s.

completed by the time the second task is ready for the bottleneck mechanism. However, note that the dependency of RT2 on RT1 is very strong at the shortest two SOAs. At the 50-ms SOA, the slope of the function relating RT2 to RT1 is .75. This is quite close to the theoretical value of 1.0, which would be predicted if the first task delays the second task on 100% of trials, and (rather unrealistically) if the variance of postcritical stages in RT1 were zero. Thus, there is clear evidence of postponement on most trials, although the slope is perhaps less than would be expected given the extremely strong interdependency.

The crucial finding of this experiment was that dual-task interference was not modulated by whether the second task involved a left-hand response to a left hemifield stimulus, or a right-hand response to a right hemifield stimulus. The SOA effect on RT2 is 214 ms for a LVF S2 and 209 ms for a RVF S2, with the interaction nonsignificant. Hence, our results show no sign of an increase in interference when the same hemisphere performed both tasks, as compared with the situation where the first task was carried out by the left hemisphere and the second task was carried out by the right hemisphere (the nonsignificant trend is actually in the opposite direction from the prediction from hemispheric resource models). In short, the usual signs of a bottleneck appeared, and with the same magnitude, whatever the hemisphere combination.

Experiment 2

The purpose of the second experiment was to test the generality of the results of Experiment 1. The present experiment differed only slightly from the first experiment. In Experiment 2, the visual-manual and auditory-vocal tasks were reversed, so the visual-manual task came first. The reason for this change is that it seems most clear that the selection and programming of the vocal response would occupy left hemisphere mechanisms (lateralization of the perceptual processing of the tone is, after all, unknown). Therefore, this ordering of the tasks might minimize involvement of the right hemisphere in the final stages of the first task.

Method

Subjects

Fifteen undergraduates at the University of California, San Diego, participated as subjects in the experiment for partial fulfillment of a course requirement. As in the previous experiments, handedness was determined using the Edinburgh inventory.

Apparatus and Stimuli

The same equipment was used in the present experiment as in the first experiment.

Design and Procedure

The design and procedure followed that of Experiment 1 exactly, except for the reversal of the tasks.

Results

Table 2 presents mean correct RTs and errors as a function of all independent variables, and Figure 3 presents RTs as a function of task and SOA, subject to the same cutoffs as in Experiment 1. The data for 1 subject were lost because of computer failure, and the data for 2 other subjects were discarded because error rates were excessive, leaving 12 subjects (4 women).

Table 2
Error Rates and Response Times (RTs, in Milliseconds [ms]) for Left and Right Responses: Experiment 2

	Stimulus onset asynchrony							
	50 ms		150 ms		500 ms		1,000 ms	
Response	RT	Error	RT	Error	RT	Error	RT	Error
Left								
R1	386	.027	393	.017	400	.016	403	.005
R2	671	—	626	—	559	—	484	—
Right								
R1	368	.023	376	.014	390	.016	387	.012
R2	663	—	623	—	549	—	486	—

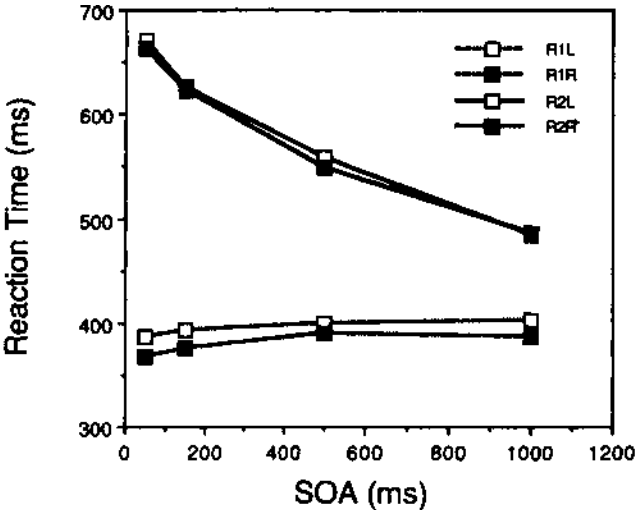

Figure 3. Experiment 2. Mean RT1 and RT2 as a function of stimulus onset asynchrony (SOA). (R1 or R2 means first or second response latency; L or R refers to whether R1 is a left- or right-hand response.)

Basic RT Effects

An analysis of variance was performed on the manual RT1 RTs. Only SOA affected RT1 significantly, *F*(3, 33) = 5.98, *p* < .005, which reflects a decrease in RT1 as SOA decreases. RT1 was faster when the stimulus was "up" (380 ms) rather than "down" (396 ms), *F*(1, 11) = 7.73, *p* < .05. It was also faster for right-hand responses (380 ms) than for left-hand responses (395 ms), *F*(1,11) = 5.46, *p* < .05. The following other effects and interactions were not significant: Up-Down X Left-Right, *F*(1, 11) < 1; Up-Down X SOA, *F*(3, 33) = < 1; Left-Right X SOA: *F*(3, 33) < 1; Up-Down X Left-Right X SOA, *F*(3, 33) < 1.

An analysis of variance was then performed on RT2 RTs. The effect of SOA was significant, *F*(3, 33) = 30.41, *p* < .001 (the PRP effect). The other factors and interactions did not show significant effects: Up-Down, *F*(1, 11) < 1; Left-Right, *F*(1, 11) < 1; Up-Down X Left-Right, *F*(1, 11) < 1; Up-Down X SOA, *F*(3, 33) < 1; Left-Right X SOA, F(3, 33) < 1; Up-Down X Left-Right X SOA, *F*(3, 33) < 1.

For RT2, the slope of the first measured segment from SOA 50 to SOA 150 was -.43.

Relationship Between RT1 and RT2

Figure 4 shows how the speed of the second response varied depending on the latency of the corresponding first response, computed as in Experiment 1. At the shorter SOAs, RT2 is more dependent on RT1 than it is at the longer SOAs, confirmed by a significant interaction of RT1 quintile and SOA, *F*(12, 132) = 6.2, *p* < .001. There was no significant interaction of RT1 quintile and left-right, *F*(4, 44) = 1.3, *p* > .25.

Errors

The only significant effect involving errors was a higher R1 error rate for left-hand responses (.056) than right-hand responses (.046).

Discussion

As in Experiment 1, typical PRP effects were observed independently of hemispheric condition; thus, there was again no evidence that the two hemispheres can act independently of one another when performing these two tasks close together in time. The results of Experiment 2 were almost identical to the results of the earlier experiment, showing no increase in interference when the left hemisphere was required to perform both tasks, as compared with the case where the first task was carried out by the right hemisphere and the second task was carried out by the left.

An additional point of interest in this experiment is the contrasting effects of right versus left R1 response in the first and second response. Right-hand RT1s were faster for these right-handed subjects than were left-hand RT1s. However, this effect does not seem to propagate onto RT2. Averaging across SOAs, left-hand RT1s are slower than right-hand RT1s by 15 ms, whereas vocal responses show only a 4-ms slowing. This result suggests that the stage in Task 1 that proceeds faster for right-hand responses is located after the bottleneck stage. It is tempting to suppose that motor response production proceeds faster for the right hand, in which case the results confirm that delays in Task 2 wait for completion of response selection, but not response production, in Task 1 (Pashler & Christian, 1992, used a much wider range of Task 1 manipulations to determine the end point of bottleneck processes in the first task). However, given the modest size of the response-hand effect, this result is merely suggestive.

Experiment 3

The first two experiments included a left-hemisphere task that required subjects to say "high" or "low" depending on

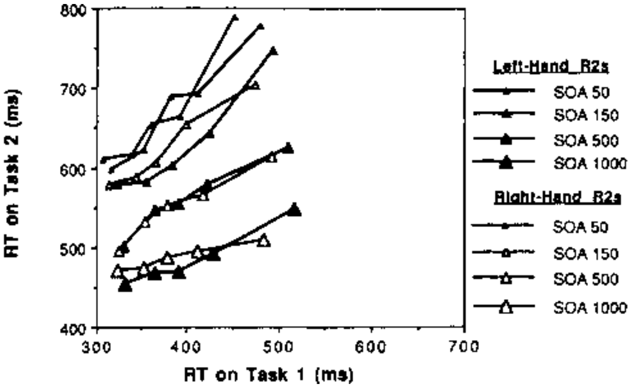

Figure 4. Experiment 2. Response time (RT) on Task 2 as a function of RT on Task 1 (broken into quintiles) as a function of stimulus onset asynchrony (SOA) and right versus left R2s.

Table 3
Error Rates and Response Times (RTs, in Milliseconds [ms]) for Left and Right Responses: Experiment 3

	Stimulus onset asynchrony							
	50 ms		150 ms		500 ms		1,000 ms	
Response	RT	Error	RT	Error	RT	Error	RT	Error
				Version A				
Left								
R1	564	—	586	—	587	—	612	—
R2	690	.012	635	.019	484	.017	395	.030
Right								
R1	563	—	583	—	597	—	608	—
R2	692	.012	639	.012	488	.016	390	.030
				Version B				
Left								
R1	605	—	605	—	624	—	633	—
R2	775	.007	700	.006	493	.016	371	.033
Right								
R1	593	—	599	—	615	—	620	—
R2	769	.009	680	.009	476	.012	363	.035

the pitch of a tone. It seemed conceivable that with a set of only two responses, vocal production might not be strongly lateralized to the left hemisphere. The present experiment required subjects to vocalize a consonant-vowel-consonant-consonant-vowel-consonant (CVCCVC) nonsense word (e.g., "VEKVUG") that was presented on the screen. A different nonsense word was presented on every trial. There is no reason to believe that the right hemisphere has any competence with the spelling-to-sound correspondence and vocal production required on such a task (Pirozzolo & Rayner, 1977; Zaidel, 1978). The second task involved responding to a disk presented either in the LVF or the RVF, exactly as in Experiment 1. If dual-task interference reflects hemisphere specific resources, we expect much greater delays for RVF disks than for LVF disks.

This experiment also helped address the possibility of eye movements. Exposures of the nonsense word and the disk were brief, and subjects found the task very difficult. Pilot work revealed that subjects found the vocal task very difficult, and made many errors even when fixating directly on the nonsense word; if one fixated a point eccentric of the disk (the only conditions under which the visual field could differ from those intended), the task became quite impossible. Subjects reported staring intently at the nonsense word.

Two versions of the experiment were run. In Version A, the hemifield in which the disk was presented (and thus the hand used for response) varied unpredictably from trial to trial. In Version B, hemifield (and response hand) was held constant within a block of trials. One might suppose that in Version A (and in the preceding experiments), the need to coordinate activity between hemispheres could preclude independent operation of the tasks in the different hemispheres condition. If so, Version B should show this independence.[1]

Method

Subjects

Twenty-four undergraduates (12 men) at the University of California, San Diego, participated as subjects in the experiment for partial fulfillment of a course requirement. As in the previous experiments, right-handedness was determined using the Edinburgh inventory. Twelve subjects served in Version A, and 12 in Version B.

Apparatus and Stimuli

The same equipment was used in the present experiment as in experiment 1. The screen was divided into four quadrants, as before, and the nonsense word was presented centered at fixation. A large set of CVCs were randomly constructed using the consonants B, G, K, P and V, and the vowels A, E, I, O and U; the first 384 CVCs that appeared reasonably pronounceable and not very similar to English words were selected. The words were 4.3 cm in width (subtending 4.1° visual angle, based on a typical viewing distance of 60 cm).

Design and Procedure

The design and procedure followed that of Experiment 1. Subjects were told that they would find the nonsense word naming task very difficult but that they should just produce the most accurate response they could, as quickly as possible. The nonsense word was exposed for 200 ms, and the disk for 100 ms. In Version A, the hemifield factor (left-right) was mixed within a block, whereas in Version B, this factor alternated between blocks (the order of blocks was counterbalanced across subjects). In Version B, sub-

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[1] We are grateful to John Duncan for suggesting this experiment.

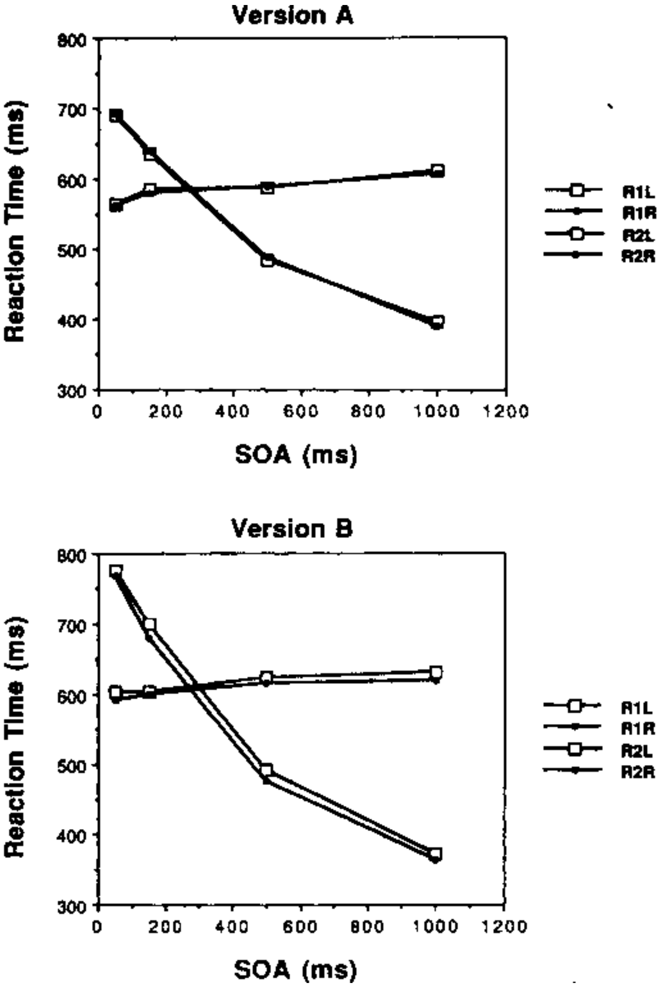

Figure 5. Experiment 3: Mean RT1 and RT2 as a function of stimulus onset asynchrony (SOA). (R1 or R2 means first or second response latency; L or R refers to whether R1 is a left- or right-hand response.

jects kept only the appropriate hand rested on the keyboard and held the microphone with the other hand.

Results

Table 3 presents mean correct RTs and errors as a function of all independent variables. Figure 5 presents RTs as a function of task and SOA, subject to the same cutoffs as in Experiment 1 (the top panel shows results from Version A, and the bottom panel shows results from Version B).

Basic RT Effects

Version A. An analysis of variance was performed on the RT1 RTs. Only SOA affected RT1 significantly. $F(3, 33) = 5.22$, $p < .005$, reflecting a decrease in RT1 as SOA decreased.

RT2 was analyzed in the same way. The SOA effect measured 299 ms, $F(3, 33) = 22.12$, $p < .001$. The only other significant effect was up-down, with faster responses for disks presented above (547 ms) rather than below (556 ms) fixation. No other factors or interactions showed significant effects: left-right, $F(1, 11) < 1$; Up-Down X Left-Right, $F(1, 11) < 1$; Up-Down X SOA, $F(3, 33) = 1.55$, $p > .20$; Left-Right X SOA: $F(3, 33) < 1$; Up-Down X Left-Right X SOA: $F(3, 33) < 1$.

For RT2, the slope of the first measured segment from 50-ms SOA to 150-ms SOA was -.53.

Version B. An analysis of variance was performed on the RT1 response times for Version B. The RTs were somewhat faster at the shortest SOA, and the effect of SOA was significant, $F(3, 33) = 13.3$, $p < .001$. No other effects were significant.

RT2 was analyzed in the same way. The effect of SOA was significant, of course, $F(3, 33) = 84.0$, $p < .001$. In addition, there was an interaction between up-down and SOA, $F(3, 33) = 4.1$, $p < .05$. This seemed to reflect primarily the fact that RTs at the shortest SOA were slower when the disk was in an upper, rather than a lower, quadrant. No other effects were significant.

For RT2, the slope of the first measured segment from the 50-ms SOA to the 150-ms SOA was -.82.

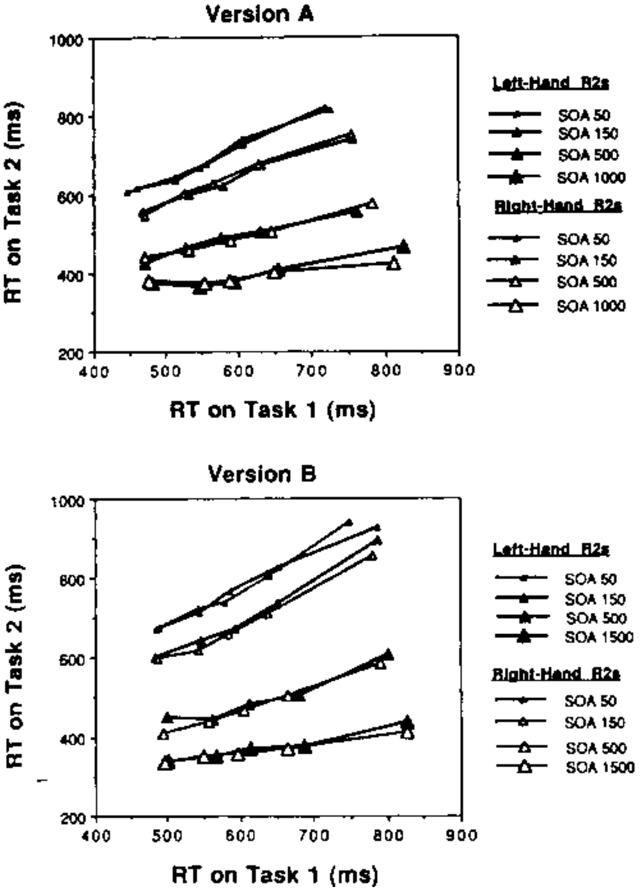

Figure 6. Experiment 3: Response time (RT) on Task 2 as a function of RT on Task 1 (broken into quintiles) as a function of stimulus onset asynchrony (SOA) and right versus left R2s.

Relationship Between RT1 and RT2

Figure 6 shows how the speed of the second response varied depending on the latency of the corresponding first response, computed as in Experiment 1 (the top panel shows Version A; the bottom panel shows Version B). At the shorter SOAs, RT2 is more dependent on RT1 than it is at the longer SOAs, confirmed by a significant interaction of RT1 quintile and SOA, $F(12, 132) = 5.2$, $p < .001$ (Version A) and $F(12, 132) = 7.9$, $p < .001$ (Version B). Crucially, there was no significant interaction of RT1 quintile and left-right, $F(4, 44) < 1$ (in both Version A and Version B).

Errors

There were no significant effects in R2 error rates in Version A. In Version B, there was some decrease in the error rate at the shorter SOAs, $F(3, 33) = 6.7$, $p < .002$.

Discussion

As in the first two experiments, very large PRP effects were observed, independent of hemispheric condition; thus, there was again no evidence that the two hemispheres can act independently of one another when performing concurrent tasks with response uncertainty. The results did not differ between Version A (hemifield mixed) and Version B (hemifield blocked). Thus, it appears that even when the subject can anticipate that only one hemifield and response hand will be used, there is still comparable interference whether the hemifield and response hand are relevant to the same or different hemispheres as that used by the concurrent task.

Experiment 4

Experiments 1-3 produced no evidence that dual-task interference with tasks requiring speeded response selection depends on whether the same cerebral hemisphere is involved in carrying out both tasks. Experiment 4 examined the question further by using two spatial tasks that would generally be presumed to be lateralized to opposite hemispheres. In the previous experiment, one stimulus was a tone; thus, it was not possible to produce input lateralized to one hemisphere exclusively. In the present experiment, two visual-manual tasks were used so that both input and output could be lateralized to a particular hemifield. In Task 1, the subject was required to respond to a disk in either the upper or lower quadrant of the LVF, making a compatible keypress response using the left hand. Task 2 required a right-hand response to a disk in the RVF. It would generally be assumed that these tasks are carried out by the right and left hemisphere tasks, respectively. Whether or not this is always the case in normal individuals, these two tasks can be carried out by disconnected hemispheres, because several split-brain patients were able to perform the identical task without difficulty (Pashler et al., 1993).

Method

Subjects

Twelve right-handed undergraduates (4 women) at the University of California, San Diego, participated as subjects in the experiment either for partial fulfillment of a course requirement or in return for payment. As in the first experiment, the Edinburgh inventory was completed by each subject to determine handedness, and only the data from right-handed subjects were used in the analysis.

Apparatus and Stimuli

The same equipment was used as in the previous experiments except for vocal response apparatus, which was not used.

Design

The experiment was divided into 12 blocks of 32 trials each, with a 2 X 2 X 4 factorial design. The first factor was whether S1 appeared in the upper or lower left quadrant of the screen in Task 1 ("left up-down"). The second factor was whether S2 appeared in the upper or lower right quadrant of the screen in Task 2 ("right up-down"). Given the compatible arrangement, the "up-down" variable pertains to both stimulus and response. The third factor was SOA. The conditions were presented to subjects in random order, with two trials per condition per block.

Procedure

As in Experiment 1, the written instructions stressed the importance of responding to each task as quickly and as accurately as possible, with grouping of the two responses discouraged. Each trial again began with the presentation of a cross as a fixation point with a duration of one second. The first stimulus (S1) was a disk (as in the preceding experiments) that appeared either in the upper left quadrant or the lower left quadrant of the display. The second stimulus (S2) was an identical disk that appeared either in the upper right quadrant or the lower right quadrant of the display. As in Experiment 1, S1 and S2 were separated by and SOA of either 50, 150, 500 or 1, 000 ms. Both the first stimulus (S1) and the second stimulus (S2) remained present for 150 ms. Subjects responded to S1 by pressing either the [a] or the [z] key, for upper or lower disks, respectively. Subjects responded to S2 by pressing either the ['] or the [/] key. As in the previous experiment, the appropriate response keys on the keyboard were quite compatible with the position of the disk on the screen.

Results

Figure 7 presents the mean RTs for correct responses as a function of task and SOA, and Table 4 presents errors and RTs broken down by all the independent variables. As in Experiment 1, RTs less than 150 ms or greater than 2,000 ms were discarded.

Basic RT Effects

An analysis of variance was performed on the RT1 response times. The effect of SOA was not significant, F(3,

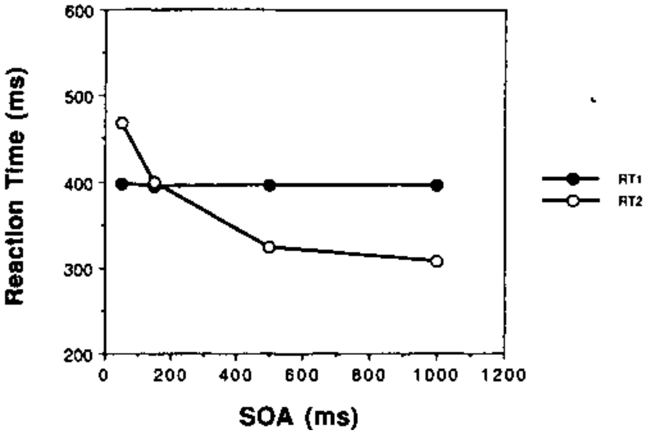

Figure 7. Experiment 4: Mean RT1 and RT2 as a function of stimulus onset asynchrony (SOA).

33) < 1. None of the other factors or interactions was significant, either.

An analysis of variance was performed on RT2s, including the same factors. SOA affected RT2 significantly, $F(3, 33) = 53.0$, $p < .001$, showing a clear-cut PRP effect. The Left Up-Down X Right Up-Down X SOA interaction was also significant, $F(3, 33) = 9.9$, $p < .001$. This reflected the more pronounced effect of the congruence of responses in the two tasks, at short SOAs.

In Figure 7, the slope of the first measured segment from the 50-ms SOA to the 150-ms SOA was -.68. This value approaches the -1 slope predicted by a bottleneck inducing postponement on all trials over this range of SOAs.

Relationship Between R1 and R2

Figure 8 presents the dependency of R2 on R1, computed as in the first experiment. This figure looks very similar to Figure 2 of Experiment 1. At the shorter SOAs R2 is more dependent on R1 than it is at the longer SOAs, confirmed by a significant interaction between RT1 quintile and SOA, $F(12, 132) = 16.8$, $p < .001$.

Errors

There were no significant effects involving either R1 or R2 errors.

Discussion

The results of this experiment again show clear-cut interference between the two hemispheres when performing two tasks close together in time. As in the same-hemisphere conditions of Experiments 1-3, we see no evidence for independent operation of the two hemispheres, nor any evidence for independent pools of processing resources.[2]

Experiment 5

The fifth experiment was conducted to check the generality of the results of Experiment 4, adding one further factor potentially favoring lateralization of performance to different hemispheres. Here, Task 1 was the same compatible spatial task on the left side that was used in the preceding experiment. The second task required the subject to determine whether a pair of words presented centrally rhymed or not. Studies by Zaidel (1978), among others, provide very strong evidence for lateralization of the grapheme-to-phoneme conversion necessary for this task to the left hemisphere.

Method

Subjects

Twelve subjects (8 women) were recruited as in the previous experiments.

Apparatus and Stimuli

The same equipment was used as in Experiment 1. S 1 was a disk, as in Experiment 1. S2 was a pair of words. The words ranged from 3 to 10 letters in length. A five-letter word was 2.5 cm wide (2.4°) and 1.1 cm high (1.0°). Half of the word pairs rhymed, and half did not. The words that rhymed were did not end with the same spelling pattern (e.g., "calf-laugh" and "enforce-coarse"). One word was presented above fixation, the other below, both centered horizontally. The vertical distance between the edges of the two words was 2.5 cm (2.4°). The screen was divided by a red cross as in Experiment 1, with the words occluding the vertical red lines. S1 was presented for 100 ms, whereas S2 remained present until both responses were recorded (the computer stopped waiting for responses after 10s).

Design

This was the same as in Experiment 4, except that the second factor was whether S2 was a rhyming or nonrhyming word pair. This factor is labeled "rhyme-no-rhyme".

Procedure

The procedure followed that of Experiment 1.

Results

Table 5 presents subjects' mean RTs and error rates for correct responses as a function of all variables.

Basic RT Effects

First, an analysis of variance was performed on RT1. The effect of SOA was significant, $F(3, 33) = 18.0$, $p < .001$, reflecting an increase in RT1 as SOA was shortened. No other RT1 effects were significant.

Second, an analysis of variance was performed on RT2. SOA affected RT2 significantly, $F(3, 33) = 111.1$, $p < .001$,

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[2] We obtained essentially the same results in another experiment in which the right hemifield stimulus was a letter (A or B) requiring a right-hand choice response.

Table 4
Error Rates and Response Times (RTs, in Milliseconds [ms]) for R1 and R2 as a Function of Stimulus Position: Experiment 4

	Stimulus onset asynchrony							
	50 ms		150 ms		500 ms		1,000 ms	
Response	RT	Error	RT	Error	RT	Error	RT	Error
R1								
Up-up	381	.010	395	.007	400	.028	390	.014
Up-down	394	.038	395	.021	394	.017	404	.007
Down-up	414	.031	398	.017	400	.007	393	.021
Down-down	396	.021	391	.004	390	.007	396	.021
R2								
Up-up	446	.028	393	.038	336	.059	322	.045
Up-down	476	.045	397	.059	310	.024	302	.035
Down-up	493	.052	409	.038	316	.045	293	.038
Down-down	456	.017	399	.042	332	.101	317	.076

reflecting a 191-ms PRP effect. The mean RT2 was 15 ms faster when the disk was up, rather than down, and oddly, this effect was reliable, $F(1, 11) = 12.9$, $p < .005$. There was also a marginally significant interaction of rhyme-no-rhyme with SOA, $F(3, 33) = 3.0$, $p < .05$, reflecting a greater advantage for no-rhyme trials at long SOAs. The slope of the first measured segment in RT2, from the 50-ms SOA to the 150-ms SOA was -.47.

Relationship Between RT1 and RT2

Figure 9 presents the dependency of RT2 on RT1. As in the earlier experiments, as SOA becomes shorter, RT2 becomes more dependent on RT1. Thus, the interaction of RT1 quintile with SOA was significant here as well, $F(12, 132) = 2.6$, $p < .005$.

Errors

There were no significant effects in error rates.

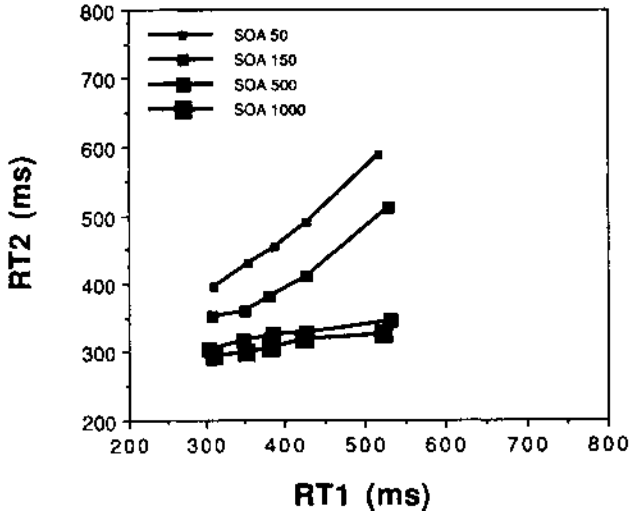

Figure 8. Experiment 4: Response time (RT) on Task 2 as a function of RT on Task 1 (broken into quintiles) as a function of stimulus onset asynchrony (SOA).

Discussion

The results show a clear-cut PRP effect, despite conditions favorable to a division of labor between the hemispheres. There were two comparatively small but significant effects on RT2 that were unexpected: an effect of whether S1 was up or down and an interaction between SOA and rhyme-no-rhyme. It is not clear how these effects should be interpreted, but they do not seem to alter the basic implications of our data.

General Discussion

In the introduction, two empirical and theoretical approaches to dual-task interference were sketched. On the one hand, studies of dual-task interference that have used tasks requiring two separate responses to two separate stimuli produced results favoring a central attentional bottleneck, but they provided no evidence about whether this bottleneck may depend upon hemisphere-specific mechanisms. On the other hand, dual-task studies inspired by hemispheric specialization data (that have found evidence for hemisphere-specific interference) have usually used tasks—such as tapping and holding verbal memory loads—that may simply not involve any bottleneck-dependent processes. The one exception, a study by Dimond (1970), did use what was intended as a refractory paradigm and claimed that the PRP effect was reduced by different-hemifield compared with same-hemifield presentation. But potentially serious problems with that study, involving lack of independent response uncertainty, and possible binocular rivalry, were noted above.

The purpose of the present studies was to try to reconcile these different conclusions by determining whether the basic bottleneck-type interference depends on hemispheric variables. The first three experiments combined a verbal (presumably left hemisphere) choice task with another task that would be assumed to rely on either the left or right hemisphere: a compatible spatial choice task with lateralized visual input and manual output. This allowed a within-subjects manipulation of same- versus different-hemisphere processing. The results of all three experiments showed

Table 5
Error Rates and Response Times (RTs, in Milliseconds [ms]) for Left and Right Responses as a Function of Whether Word Pair Rhymed: Experiment 5

	Stimulus onset asynchrony							
	50 ms		150 ms		500 ms		1,000 ms	
Response	RT	Error	RT	Error	RT	Error	RT	Error
R1								
Rhyme	462	.047	428	.045	399	.017	416	.030
No rhyme	453	.033	426	.021	399	.026	405	.033
R2								
Rhyme	1,290	—	1,261	—	1,137	—	1,128	—
No rhyme	1,306	—	1,242	—	1,140	—	1,088	—

dramatic PRP-type interference, the magnitude of which was unaffected by whether the tasks used the same hemispheres or different hemispheres. Analyses of interresponse dependencies showed no sign that hemispheric condition made any difference to the underlying postponement process. The results were unchanged when the input hemifield and response hand was held constant from trial to trial, in Version B of Experiment 3.

Experiments 4 and 5 examined pairs of tasks with both input and output lateralized to opposite hemispheres. In Experiment 4, both tasks required a compatible response to spatial position (above vs. below the horizontal midline). Experiment 5 included the spatial task as Task 1 (with LVF presentation and left-hand response) and a rhyme judgment as Task 2. In both cases, the effects of SOA and the interresponse dependencies indicated that the bottleneck persisted.

Together with previous research, these conclusions implicate a bottleneck in action selection, but they indicate that the bottleneck is in some ways anatomically, as well as functionally, central (e.g., Pashler & Johnston, 1989; Welford, 1952). There is no indication that the standard hemispheric manipulations of stimulus, response, and form of coding can moderate (much less eliminate) this bottleneck by permitting resources or mechanisms in different hemispheres to function independently. Earlier proposals might lead one to expect such independence (Dimond, 1970; Friedman & Polson, 1981; Friedman et al. 1982; Kinsbourne & Hicks, 1978).

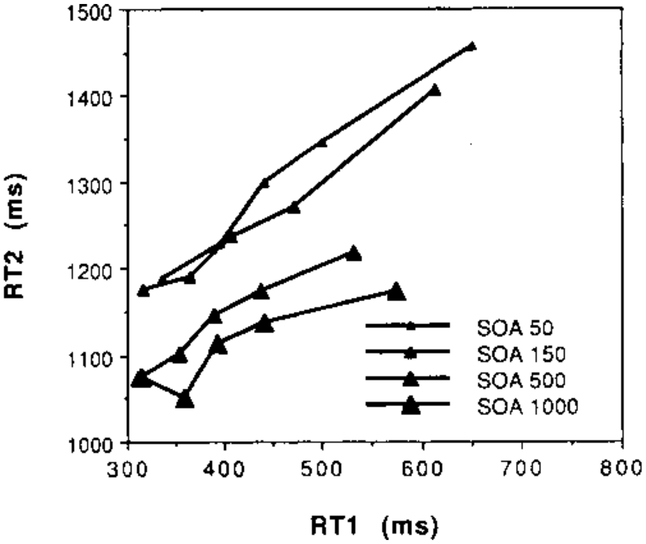

Figure 9. Experiment 5: RT2 as a function of RT1 (broken into quintiles) as a function of stimulus onset asynchrony (SOA).

This conclusion raises two very intriguing questions. First: Can one infer anything about the neural basis for the bottleneck, given that postponement of processing occurs whether or not the same cerebral hemispheres are required for the tasks? Second: How can these results be reconciled with the reliable effects of same- versus different-hemisphere processing found in previous research?

The Neural Bases of the Bottleneck

Why should the two hemispheres carry out critical operations sequentially rather than carrying them out in parallel? (Based on previous research, one can assume that these operations include response selection, although it seems they may sometimes include other operations, such as motor programming; see Pashler & Christian, 1992.) One possible answer is that even when each hemisphere is perfectly capable of carrying out the critical operations by itself, the activity in one hemisphere nevertheless inhibits comparable activity in the other hemisphere. This inhibition might depend on either callosal or subcortical pathways (preliminary data from split-brain patients seems to be favoring the latter possibility; see Pashler et al., 1993). This form of inhibition or mutual "lock-out" of processing could be a general principle of cortical function that serves to prevent the possibility of disruption or crosstalk; thus, it might operate even with specific tasks that are not in fact likely to disrupt each other.

With regard to this last point, the comparison between Experiments 1 and 4 is interesting. In Experiment 4, the two tasks seem ideally chosen to disrupt each other by activating competing responses (Navon & Miller, 1987), because except for horizontal position, each stimulus could as well serve as the input for the other task, in which case it would lead to the wrong response on half the trials. However, evidence of a bottleneck was just about as pronounced in Experiment 1, where the stimuli and stimulus modalities, the nature of the mapping, and the responses and response modalities in the two tasks were all different.

Another possibility is that the critical bottleneck stages of the two tasks are not in fact carried out in different hemispheres. Rather, in intact individuals, they may be carried out by the distributed activity of both hemispheres. Even if this is correct, the results still limit the generality of the separate hemispheric resources hypothesis (Friedman & Polson, 1981) or Dimond's (1970) related hypothesis. After all, these authors did propose that manipulations of the sort we have used (hemifield, response side, verbal vs. spatial processing) are capable of determining which hemisphere controls the resources needed by a task and thereby reducing interference. Thus, at the very least, the present results require that the conclusions of those researchers be narrowed to pertain to mental operations other than those involved in the bottleneck.

Finally, it might be the case that subcortical, rather than cortical mechanisms, actually carry out the critical bottleneck operations in both tasks, thus producing postponement that is independent of the cerebral hemispheres involved. Recent work of Osman and Moore (1990) may provide some hints about this issue. They examined event-related brain potentials while subjects carried out a PRP task. The lateralized readiness potential in Task 2 (a potential that appears over motor cortex shortly prior to a contralateral response) was delayed at shorter SOAs, and paralleling the delays observed in the Task 2 response (i.e., the PRP effect). So it seems that the PRP effect does not originate in stages that occur only after all cortical involvement is complete. Of course, this is not inconsistent with the possibility just discussed, that subcortical structures carry out the bottleneck stage, assuming that this were followed by further response-related cortical activity.

Given this range of very intriguing possibilities for the underlying causes of the bottleneck, strong conclusions about how the hemispheres (and subcortical structures) coordinate two response selections would clearly be premature at the moment.

Reconciling the Results With Hemispheric Findings

Finally, we turn to the question of why other investigators have observed dual-task interference to be exacerbated when tasks were performed by the same hemisphere, rather than different hemispheres. As noted in the introduction, the tasks these investigators have used are known or suspected not to produce bottleneck effects on a concurrent task. Examples include repetitive finger tapping, retention of verbal memory loads, verbal comprehension and various perceptual judgment tasks.

It is not difficult to think of ways in which these findings might potentially be reconciled. Some of the non-bottleneck-dependent activities may not fully occupy any cortical machinery at all; rather, they may change the state of the machinery so that it carries out other tasks less efficiently. For example, maintaining a verbal memory load (during periods in which active rehearsal is not taking place) might depend on transient synaptic changes in the left hemisphere that introduce undesirable noise when that hemisphere carries out other activities. Although tapping seems dependent on intactness of certain cortical areas (Kolb & Wishaw, 1985), it might involve neural activity that is confined to a very limited region of cortex. This might, for example, be some form of reverberatory activity, which in turn could produce graded interference with any processes that depended on large portions of the same hemisphere. (This suggestion is similar to that of Kinsbourne, 1981. Naturally, there are many other possible ways in which tapping or holding a memory load might produce interference that is both hemisphere-specific and partial.)

From the present results, though, it seems possible that bottleneck-type interference might reflect recruitment of a great deal of the cortex into the process of selecting a response or retrieving an item from memory, or the "locking out" of such processes wherever they take place, as discussed in the preceding section. One clear implication of the present results is that future studies of hemispheric factors in dual-task interference ought to be targeted to particular processing stages and operations, because it seems that conclusions relevant to one set of operations may not apply to others. In particular, it seems that when response uncertainty is present in both tasks, one finds quite a different pattern of dual-task interference from that arising in situations where this critical feature is lacking.

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