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The Cerebral Hemispheres Cooperate to Perform Complex but not Simple Tasks

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Three experiments were designed to examine whether task complexity determines the degree to which a division of processing across the hemispheres (i.e., across-hemisphere processing) underlies performance when within- and across-hemisphere processing are equally possible. When task complexity was relatively low, performance in a midline condition that allowed for either within- or across-hemispheric processing resembled within-hemisphere performance (Experiments 1 and 2). However, when task complexity was high, performance in a midline condition (Experiments 1 and 2) and a lateralized condition, which also allowed for either within- or across-hemisphere processing (Experiment 3), resembled across-hemisphere performance. Results complement and extend prior work (e.g., M. T. Banich & A. Belger, 1990) by indicating that the degree to which interhemispheric cooperation underlies performance changes with the complexity of the task being performed. This finding suggests that the hemispheres dynamically couple or uncouple their processing as a function of task complexity.

Although numerous studies have demonstrated that the cerebral hemispheres process information in different ways (e.g., Sperry, 1974), relatively few have explored how the hemispheres coordinate their processing and the effect that such coordination has on task performance (e.g., Banich & Belger, 1990; Liederman, 1986). Given that each hemisphere is a somewhat independent processor (Friedman & Polson, 1981), dividing and coordinating processing across the hemispheres may be advantageous in certain situations. A division of processing across the hemispheres would provide more computational power than would a division of processing within a hemisphere because it would allow more independent brain regions to be recruited for task performance (Banich & Belger, 1990). Furthermore, the increase in computational power afforded by interhemispheric cooperation might be especially beneficial for complex tasks that require relatively large numbers of computations (e.g., Banich & Belger, 1990; Belger & Banich, 1992).

Consistent with this view, we and others have reported that interhemispheric cooperation facilitates the performance of computationally complex tasks more than it aids the performance of simpler tasks (Banich & Belger, 1990; Banich & Passarotti, 1999; Belger & Banich, 1992, 1998; Copeland & Zaidel, 1996; Passarotti & Banich, 1999; Weissman & Banich, 1999, in press; Yoshizaki & Tsuji, 1998). The crucial finding in these studies is that as task complexity increases, it becomes more advantageous to divide the items critical for reaching a decision between the hemispheres (across-hemisphere processing) than to direct them to the same hemisphere (within-hemisphere processing). For example, relatively simple tasks, such as deciding that two items are perceptually identical, are often performed better when the critical items are directed to the same hemisphere rather than to different hemispheres (e.g., Banich & Belger, 1990; Banich & Passarotti, 1999). More complex tasks, however, are performed better when the two critical items are directed to different hemispheres, compared with when they are directed to the same hemisphere (see Banich, 1998, for a review). This effect has been observed for a variety of complex tasks that include deciding whether one digit's value is less than another's (Banich & Belger, 1990, Experiment 3), deciding that two letters have the same name (e.g., *A* and *a*; Banich & Belger, 1990, Experiment 1), deciding that two geometric forms have the same shape even though they differ in color (Banich & Passarotti, 1999), and deciding that two hierarchical stimuli are identical at a prespecified level (e.g., local) even though they differ at the irrelevant level (e.g., global; Weissman & Banich, 1999).

Interestingly, the data suggest that the effects of interhemispheric interaction on performance change gradually with task complexity. For example, a large within-hemisphere advantage sometimes shifts to a reduced within-hemisphere advantage or to no difference between within- and across-

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hemisphere processing as task complexity increases rather than shifting to a significant across-hemisphere advantage (e.g., Weissman & Banich, in press). In other cases, a small across-hemisphere advantage becomes a larger one as task complexity increases (e.g., Belger & Banich, 1992). Regardless of the baseline, however, the efficiency of across-hemisphere processing, relative to that of within-hemisphere processing, increases as tasks become more complex (but see Banich, 1995, for a discussion of ceiling effects on the across-hemisphere advantage).

Although some data in the literature are seemingly inconsistent with these findings, a closer examination reveals that these discrepancies can likely be attributed to methodological differences between our paradigm and those used by other investigators. For example, several investigators have reported robust across-hemisphere advantages even for relatively simple tasks, such as physical-identity letter-matching tasks, for which we frequently have found within-hemisphere advantages (e.g., Brown & Jeeves, 1993; Hellige, 1987; Ludwig, Jeeves, Norman, & DeWitt, 1993). In the studies showing an across-hemisphere advantage for the physical-identity task, however, only two task-relevant items are presented on each trial. Thus, the robust across-hemisphere advantages reported in these studies may have occurred because each hemisphere received a lighter load on across-hemisphere trials (i.e., only one task-relevant item) than a single hemisphere received on within-hemisphere trials (i.e., two task-relevant items). In our studies, we typically use three-item displays, in which every item is task relevant, to avoid this possibility (see examples of within- and across-hemisphere trials in Figure 1). In our displays, the processing load per hemisphere is identical on within- and across-hemisphere trials (i.e., two items to one hemisphere, one item to the other hemisphere). Because each hemisphere receives the same number of task-relevant inputs on within- and across-hemisphere trials, an across-hemisphere advantage cannot occur as a result of each hemisphere receiving a lighter load on across-hemisphere trials than a single hemisphere receives on within-hemisphere trials. Thus, the discrepancy between our findings and those of other investigators is likely due to the fact that our paradigm equates the processing load per hemisphere on within- and across-hemisphere trials, whereas other paradigms do not.

Of importance, there is also evidence to suggest that the within- and across-hemisphere advantages that we observe in our three-item paradigm are not artifacts produced by using this type of display. For example, one might consider the possibility that a within- or across-hemisphere advantage obtained in our three-item paradigm is driven by the order in which the comparisons are made between the bottom target item and the two top probes.[1] This scenario seems improbable, however, given Copeland's (1995) finding that cuing the items to be compared in a three-item paradigm does not influence the degree to which interhemispheric cooperation facilitates or hinders performance for either the physical-identity (PI) or the name identity (NI) task. Further evidence that our results are not artifacts of our arrays comes from a recent study we performed with four-item displays, in which each hemisphere received two task-relevant items, one target and one probe (Weissman & Banich, in press). With these arrays, we also found that interhemispheric interaction facilitates performance more for relatively complex tasks than for relatively simple ones.

Banich and colleagues (e.g., Banich, 1995; Banich & Belger, 1990; Banich & Passarotti, 1999; Weissman & Banich, 1999) have suggested that the dynamic effect of interhemispheric cooperation on performance may be explained by an interaction between two opposing forces. On the one hand, interhemispheric cooperation is likely to increase the computational power of task performance because each hemisphere can process information somewhat independently of its partner (Friedman & Polson, 1981). On the other hand, interhemispheric cooperation likely incurs time costs not associated with intrahemispheric processing because it requires that information be integrated between the hemispheres by way of the corpus callosum. When task complexity is relatively low, the benefits associated with greater computational power are not great enough to outweigh the costs associated with integrating information across the hemispheres, leading to a within-hemisphere advantage. However, when task complexity is relatively high, the benefits associated with greater computational power become more substantial than the costs incurred by integrating processing between the hemispheres, leading to an across-hemisphere advantage. Thus, in our view, the relative efficiency of within- and across-hemisphere processing changes as a function of task complexity.

Our model of interhemispheric interaction incorporates many assumptions made by other models but is distinct because of its emphasis on the greater computational power afforded by a hemispheric division of processing. First, similar to other models (e.g., Liederman, 1986; Sohn, Liederman, & Reinitz, 1996), we assume that a division of processing across the hemispheres may facilitate performance by regulating cross-talk between conflicting processes (Shenker & Banich, 1999). We have also found, however, that a hemispheric division of processing facilitates performance for complex tasks even when no obvious conflicting processes are present (e.g., in the five-item physical identity task used by Belger & Banich, 1992) and when stimulus information that engenders conflicting processes is directed to the same hemisphere (Weissman & Banich, 1999). Second, we incorporate the assumption that hemispheric differences may constrain the outcome of interhemispheric interaction (e.g., Robertson, Lamb, & Zaidel, 1993). We have argued, however, that such constraints operate mainly when only one hemisphere can perform a task, in which case an across-hemisphere advantage may not be observed (e.g., Belger & Banich, 1998). When both hemispheres can perform a task, hemispheric differences in processing generally do not constrain, or even predict, the outcome of interhemispheric processing (e.g., Weissman & Banich, 1999; see Banich, 1995, for a discussion). Third, in our model, we acknowledge that interhemi-

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[1] This possibility was raised by an anonymous reviewer.

spheric interaction is not a unitary phenomenon, in the sense that different tasks may require that different types of information be transferred across the corpus callosum (e.g., Nicholas & Marsolek, 1997). Nevertheless, interhemispheric interaction becomes more advantageous to performance as task complexity increases in several sensory modalities, each of which involves transfer of information across a different channel of the callosum (Passarotti & Banich, 1999). Thus, although many factors may contribute to the across-hemisphere advantage observed for complex tasks, a major determinant of the across-hemisphere advantage appears to be the gain in computational power associated with a distribution of processing across brain regions in both hemispheres.

Although it has been demonstrated experimentally that interhemispheric interaction can aid performance for computationally complex tasks, relatively little is known about when across-hemisphere processing occurs under more naturalistic conditions in which within- and across-hemisphere processing are equally possible. In prior studies, experimenters constructed the stimulus arrays so that certain trials necessitated interhemispheric interaction (across-hemisphere trials) and others did not (within-hemisphere trials). Even though comparing performance on within- and across-hemisphere trials allows one to determine whether across-hemisphere processing is advantageous to performance relative to within-hemisphere processing, it does not allow one to determine which processing mode (within- or across-hemisphere) is used when either is possible. This question is of particular interest, however, because in most nonlaboratory situations, information is simultaneously available to both hemispheres. Whenever a stimulus is seen in central vision, heard nondichotically, or touched by both sides of the body, it is sent directly to both halves of the brain. Thus, the brain normally receives information in a way that allows either within- or across-hemisphere processing to underlie performance.

Although far from definitive, several findings suggest that when within- and across-hemisphere are equally possible, the processing mode underlying performance changes dynamically with task complexity. First, neuroimaging studies of neurologically intact populations indicate that unilateral activity (which may reflect within-hemisphere processing) is often observed for relatively simple tasks, whereas bilateral activity (which may reflect across-hemisphere processing) is often observed for relatively complex tasks (e.g., Klingberg, O'Sullivan, & Roland, 1997). Second, relative to younger adults, older adults exhibit both greater bilateral activation in neuroimaging studies (e.g., Reuter-Lorenz et al., 1996) and greater benefits from interhemispheric interaction in behavioral studies (Reuter-Lorenz, Stanczak, & Miller, in press). Thus, having both hemispheres involved in processing may be a strategy used by the aging brain to cope with diminished capacity (Reuter-Lorenz et al., in press). Third, relative to controls, split-brain patients often exhibit greater performance impairments as task complexity increases (e.g., Kreuter, Kinsbourne, & Trevarthen, 1972). In the absence of the corpus callosum, performance impairments for complex tasks may occur because processing cannot be easily distributed across both hemispheres. In sum, the evidence to date is highly consistent with our present hypothesis that when either processing mode is possible, within-hemisphere processing underlies the performance of relatively simple tasks and across-hemisphere processing subserves the performance of more complex tasks.

Even though the findings above are suggestive, there are issues associated with each that limit their interpretability. With respect to the neuroimaging studies, more bilateral activity for a relatively complex task than for a simpler one need not reflect increased amounts of interhemispheric cooperation. First, bilateral activity could reflect each hemisphere working independently on a task, as suggested by certain horse-race models (e.g., Zaidel & Rayman, 1994). Second, more bilateral activity for one task than for another could reflect differences in the representations and their associated neural processors that are used to perform the tasks. For example, encoding nameable objects (which likely involves using both verbal and visuospatial representations) evokes bilateral prefrontal activity. In contrast, encoding verbal material or unfamiliar faces evokes more unilateral prefrontal activity, as each involves only one type of representation (verbal and visuospatial, respectively; e.g., Kelley et al., 1998). Third, greater bilateral activation for a complex task than for a simpler task may result because the extra processes needed to perform the complex task are in the opposite hemisphere from the processes that underlie performance for the simpler task. By this account, bilateral activity reflects mandatory rather than optional recruitment of both hemispheres to performance. Fourth, age differences in the degree to which bilateral activation is observed may reflect differences in processing strategy rather than differences in some kind of optional neural recruitment. It is well known, for example, that older populations tend to be more careful in their decision making than are younger populations (e.g., Strayer & Kramer, 1994). Extra processing due to the use of different processing strategies might well account for some of the additional bilateral activation found in older as compared with younger participants. Therefore, although suggestive, none of the above findings provide conclusive proof that interhemispheric interactions vary dynamically with task complexity.

Findings from neurologically impaired populations, such as split-brain patients, can also be difficult to interpret definitively. For example, split-brain patients sometimes exhibit impaired dual-task performance relative to a single-task baseline, compared with controls (e.g., Kreuter et al., 1972). One interpretation of the superior performance in intact individuals is that the callosum normally serves to distribute processing across both hemispheres when task complexity is high. Because commisurotomy precludes such a distribution, split-brain patients exhibit impaired performance. Another possible interpretation, however, is that dual-task situations require executive processes to coordinate the simultaneous performance of two tasks in addition to those processes required by each single task in isolation. These additional processes may be disrupted in split-brain patients because of their history of frequent epileptic seizures, which are associated with diffuse brain injury. Hence, it may be difficult to determine whether the deficits found in split-brain patients are due to impaired interhemispheric communication or to other forms of brain damage. Therefore, although such studies are highly suggestive of the possibility that processing is typically distributed across both hemispheres for complex tasks, they are not definitive.

Our present hypothesis is also consistent with findings from studies of metacontrol (e.g., Hellige & Michimata, 1989; Hellige, Taylor, & Eng, 1989; Levy & Trevarthen, 1976; Luh & Levy, 1995). Metacontrol refers to a situation in which "one hemisphere in some sense dominates processing when both have equivalent access to relevant stimulus input" (Hellige et al., 1989, p. 711). The motivation for these studies has been quite similar to that for our present experiments, except that these other studies investigate which of the two hemispheres, the right or the left, dominates task performance when both receive stimulus input. In contrast, our experiments investigate whether a single hemisphere or both hemispheres working together dominate task performance when either is possible. Because these previous studies influenced the rationale for our methods and data analyses and because some of the conclusions drawn from these previous studies are consistent with our present hypothesis, we now describe them in detail.

Studies of metacontrol in neurologically intact populations typically measure performance in three conditions: a right visual field–left hemisphere (RVF–LH) condition, a left visual field–right hemisphere (LVF–RH) condition, and a bilateral condition. It is assumed that either hemisphere can underlie performance in the bilateral condition because two identical copies of the stimulus are presented: one to the LVF and the other to the RVF. Furthermore, performance in the LVF, RVF, and bilateral conditions is always measured across the levels of a second variable (e.g., type of response: match or mismatch). Hellige and colleagues (Hellige et al., 1989) have argued that if the pattern of performance produced by manipulating the second variable (e.g., the difference in reaction time for match and mismatch trials) varies for the RVF–LH and LVF–RH conditions, then there is a hemispheric difference in processing. Furthermore, one may determine which hemisphere underlies performance on bilateral trials by examining whether the pattern of performance caused by manipulating the second variable resembles that on RVF–LH trials or that on LVF–RH trials. It is important to notice that the logic of this approach relies on a processing dissociation. One concludes that performance in one condition (i.e., the bilateral condition) is subserved by the same mechanism that underlies performance in another condition (e.g., the RVF–LH condition) when the pattern of performance produced by a second variable is similar for these two conditions but differs for a third (e.g., the LVF–RH condition).

The findings from these studies have indicated that the pattern of performance on bilateral trials sometimes resembles that on RVF–LH trials, sometimes resembles that on LVF–RH trials, and sometimes is unique. For example, Hellige and Michimata (1989) found that the pattern of performance on bilateral trials produced by varying the nature of the response in a letter-matching task (i.e., match vs. mismatch) resembled that on RVF–LH trials and differed significantly from that on LVF–RH trials. In another study, however, Hellige et al. (1989) found that the qualitative nature of errors in a consonant-vowel-consonant identification task for bilateral trials resembled that on LVF–RH trials and differed significantly from that on RVF–LH trials. Moreover, performance on bilateral trials mimicked that on LVF–RH trials even though overall error rates were lower on RVF–LH trials. This latter finding is important because it demonstrates that the hemisphere that underlies performance is not always the one that is most efficient for performing a task. Finally, other studies have found that the pattern of performance on bilateral trials differs from that on both LVF–RH trials and RVF–LH trials (e.g., Banich & Karol, 1992; Eng & Hellige, 1994). This finding is consistent with our present hypothesis because it suggests that when both hemispheres receive stimulus information, performance may sometimes be driven by both hemispheres working together rather than by a single hemisphere.

In summary, multiple independent lines of evidence are consistent with our present hypothesis that when within- and across-hemisphere processing are equally possible, the most efficient mode of processing underlies performance. None of these findings is conclusive, however. In the present study, therefore, we adopted the logic of processing dissociations used by Hellige and colleagues (Hellige et al., 1989) to investigate our hypothesis in three experiments.

Experiment 1

In Experiment 1, we investigated whether the degree to which interhemispheric cooperation underlies performance varies dynamically with task demands by using a variant of Banich and Belger's (1990) three-item paradigm. As in Banich and Belger's study, participants performed two tasks that varied in terms of computational complexity. In the less complex PI task, participants determined whether a target letter presented beneath fixation was perceptually identical to one of two probe letters presented above fixation (e.g., *A* and *A*; see Figure 1). In the more complex NI task, participants determined whether a lowercase letter beneath fixation had the same name as one of two uppercase letters above fixation (e.g., *a* and *A*; see Figure 2). The NI task is more complex than the PI task because in addition to the perceptual processing of the items that is required in the PI task, the categorical identity of each item must be determined for the task to be performed correctly.

The PI and NI tasks are well-suited for exploring our present hypothesis because data from split-brain patients indicates that each of these tasks can be performed equally well by the right and left cerebral hemispheres of the brain (Eviatar & Zaidel, 1994). Thus, in neurologically intact individuals, it is likely that each task can be performed either by a single hemisphere working in relative isolation (within-hemisphere processing) or by both hemispheres working together (across-hemisphere processing). Our hypothesis predicts that when either processing mode is possible, across-hemisphere processing should underlie performance for the relatively complex NI task, whereas within-hemisphere processing should underlie performance for the simpler PI task.

To test our hypothesis, the performance of each task was measured in three conditions of interest: a within-hemisphere condition, an across-hemisphere condition, and a midline condition. On within-hemisphere match trials, the matching items were presented to the same visual field and, hence, to the same hemisphere. Therefore, no interhemispheric cooperation was required to reach a match decision. In contrast, on across-hemisphere match trials, the matching items were presented to different visual fields and, hence, to different hemispheres. Thus, interhemispheric cooperation was required to reach a match decision. Finally, on midline match trials, the matching probe item was lateralized to one visual field, whereas the target item was presented on the midline. As we explain below, either within- or across-hemisphere processing could underlie performance on midline trials.

Information presented on or near the midline may be available to both hemispheres through a variety of mechanisms. First, it may be bilaterally represented in the primary visual cortex, although some data suggest that bilateral representation of the fovea is fairly weak in humans (Fendrich, Wessinger, & Gazzaniga, 1996) or may not even exist at all (Sugishita, Hamilton, Sakuma, & Hemmi, 1994). Second, it may become available to both cerebral hemispheres because of small (less than ⅓ of a degree, on average) microsaccades around the fixation point that can be made in far less than the 200-ms stimulus duration we used (Carpenter, 1988). Third, if the foveal area is effectively divided between the hemispheres, then an item on the midline may become fully available to both hemispheres only following interhemispheric integration of the item across the hemispheres. In all of these cases, however, the bottom item comes to be represented in both hemispheres. Thus, within-hemisphere processing could underlie the match decision on midline trials if the hemisphere that receives the lateralized matching probe also takes the lead for processing the midline item. Across-hemisphere processing could underlie the match decision on midline trials, however, if the hemisphere that does not receive the lateralized matching probe takes the lead for processing the midline item.

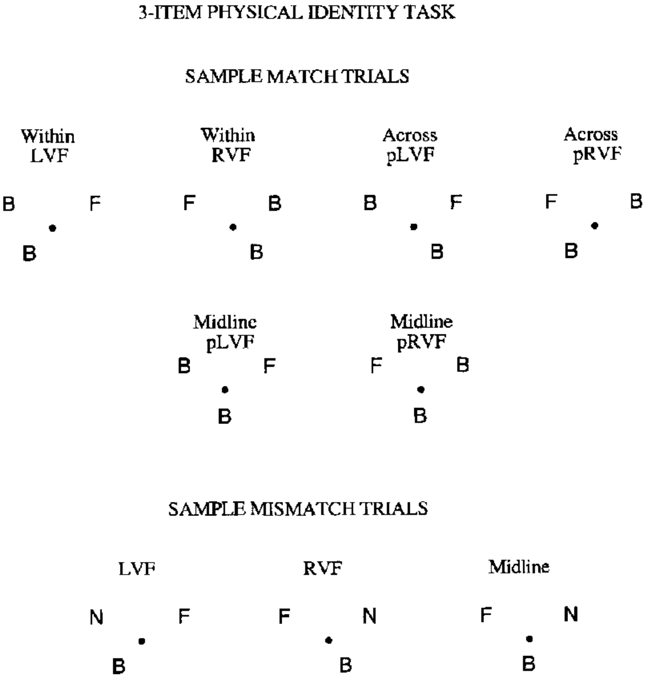

Figure 1. Sample match and mismatch trials for the physical-identity task in Experiments 1 and 2. Participants were asked to decide whether the bottom target item was perceptually identical to one of the top probe items. In Experiment 1, the stimuli were black letters on a white screen, whereas in Experiment 2, they were white letters on a black background. LVF = left visual field; RVF = right visual field; p = position of top matching probe.

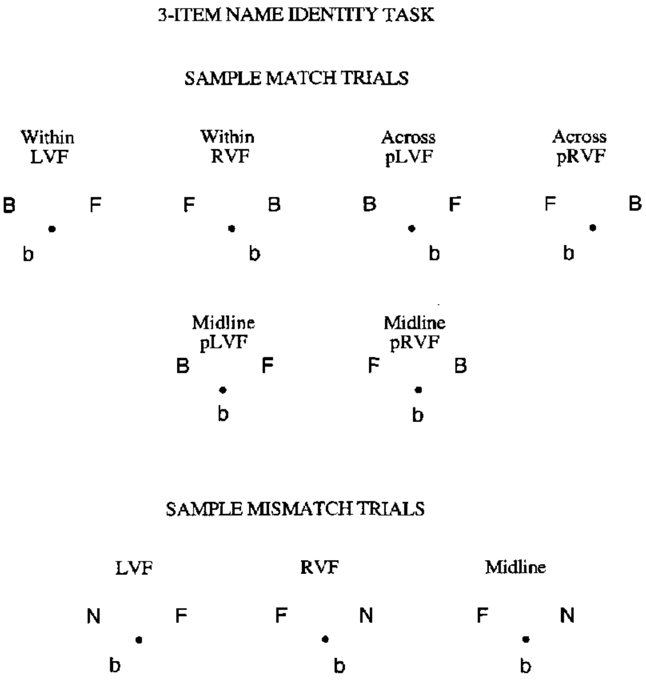

Figure 2. Sample match and mismatch trials for the name-identity task in Experiments 1 and 2. Participants were asked to determine whether the bottom item had the same name as one of the top two probe items. In Experiment 1, the stimuli were black letters on a white background, whereas in Experiment 2, they were white letters on a black background. LVF = left visual field; RVF = right visual field; p = position of top matching probe.

Our present hypothesis led us to predict that the pattern of performance on midline trials would be distinct from that on within- and across-hemisphere trials. More specifically, we predicted that the increase in reaction time and error rates going from the PI task to the NI task would be smallest on across-hemisphere trials, intermediate on midline trials, and largest on within-hemisphere trials. The intermediate pattern on midline trials was predicted because we expected that performance in the midline condition would resemble within-hemisphere performance for the less complex PI task (which often yields a within-hemisphere advantage) but would resemble across-hemisphere performance for the more complex NI task (which usually yields an across-hemisphere advantage).

Method

Participants. Twenty-four right-handed University of Illinois students (12 men, 12 women) with normal or corrected-to-normal vision were paid $5 or received course credit for participating in the experiment.

Stimuli. The stimuli were seven uppercase letters (*A, B, D, F, G, H,* and *N*) and their lowercase counterparts. The uppercase letters were displayed in Geneva 38-point bold font. The lowercase letters were displayed in Geneva 44-point bold font to make them more equivalent to the uppercase letters in terms of size and discriminability. All stimuli subtended a maximum of 1° of visual angle horizontally and vertically. In each trial, three stimuli were presented. The target letter was centered 2° beneath fixation, either 2° to the left, 2° to the right, or on the midline. Two probe letters were centered 2° above fixation, one 4° to the left and the second 4° to the right.

We used a three-item display to equate the perceptual load directed to each hemisphere on within- and across-field trials (i.e., one hemisphere always receives two items, whereas the other receives just one). In addition, the matching items for both within- and across-hemisphere were presented with a diagonal rather than horizontal alignment. This arrangement was used to preclude the possibility that reading strategies used with horizontal arrangements might influence performance for either trial type (e.g., Ludwig et al., 1993; see Banich & Shenker, 1994, for a fuller discussion of these issues).

All stimuli were displayed as black letters on a white background. A Macintosh Centris 650 equipped with a 14-in. (35.6-cm) color monitor and SuperLab software (Cedris Corporation, Silver Spring, MD) was used to present the stimuli and to collect participants' responses.

Procedure. First, we assessed participants' handedness using a 16-item questionnaire that determined the hand used most often by participants to perform several common tasks (e.g., tearing off the lid of a package, writing, and so forth). Next, we screened participants for possible visual problems. Right-handed participants with normal or corrected-to-normal vision then performed two tasks. In the PI task, participants decided if the target item beneath fixation was perceptually identical to one of the two probe items above fixation (e.g., *A* and *A*). In the NI task, participants decided if the target item had the same name as one of the probes (e.g., *A* and *a*). On each trial of both tasks, participants first viewed a fixation dot for 500 ms. Next, the stimulus array appeared for 200 ms. Participants used their index finger to press one computer key (e.g., the "G" key) if the target matched either probe (50% of trials) and their middle finger from the same hand to press another key (e.g., the "H" key) if the target matched neither probe (50% of trials). Hand was counterbalanced within participants and response key-decision mappings were counterbalanced across participants.

On within-hemisphere match trials, no interhemispheric interaction was required because both matching items appeared in the same visual field, either in the left visual field (within-LVF trials) or in the right visual field (within-RVF trials). On across-hemisphere match trials, interhemispheric interaction was required because matching items appeared in different visual fields, either with the target in the RVF and probe in the LVF (across-pLVF trials) or with the target in the LVF and probe in the RVF (across-pRVF trials). As discussed earlier, on midline trials, within- and across-hemisphere processing were equally possible because the target item was presented on the midline. On midline pLVF trials, the matching probe was presented in the LVF, whereas on midline pRVF trials, the matching probe was presented in the RVF. The different trial types—within LVF, within RVF, across pLVF, across pRVF, midline pLVF, and midline pRVF—appeared equally often as match trials (no distinction between these trial types was possible in mismatch trials as can be seen in Figures 1 and 2). Furthermore, to preclude a response bias from developing on the basis of an item's position in the display, each stimulus appeared in each possible location an equal number of times on match and mismatch trials. All participants performed the PI task first and the NI task second to minimize the possibility that they would compare letters in terms of name identity in the PI task. There were 48 practice trials and 336 test trials for each task.

Table 1
Mean Reaction Times (in Milliseconds) and Mean Percentage Error Rates (in Parentheses) in Experiment 1

Interhemispheric condition	Task: Physical identity	Task: Name identity
Within		
LVF	403 (7.6)	544 (13.2)
RVF	416 (5.7)	581 (17.7)
Average	410 (6.6)	562 (15.5)
Across		
pLVF	418 (8.5)	462 (8.5)
pRVF	432 (10.7)	517 (11.5)
Average	425 (9.6)	489 (10.0)
Midline		
pLVF	391 (4.3)	503 (9.1)
pRVF	412 (6.5)	522 (12.2)
Average	401 (5.4)	512 (10.6)

Note. LVF = left visual field; RVF = right visual field; p = the position of the top matching probe (e.g., pLVF means that the matching probe was in the LVF).

Results

We performed separate repeated measures analyses of variance (ANOVAs) on average reaction times (RTs) for correct match trials and average error rates for match trials with the following within-participants variables: task (PI, NI), interhemispheric condition (within, across, midline), and visual field of matching probe (LVF, RVF).[2] All response times reported in this article were measured from stimulus offset to response. Furthermore, reaction times with latencies greater than 1,500 ms were treated as errors. Average RTs and error rates for Experiment 1 are reported in Table 1.

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[2] In another set of analyses, the RT data for all three experiments were log transformed to reduce the correlation between means and standard deviations that normally characterize RT distributions. The error rate data for all three experiments were also transformed using an arcsine transformation. Because the interhemispheric effects we observed were present in both the untransformed and the transformed data, we chose to report the untransformed data so that our data would be more easily compared with previously published reports in the literature.

RT. As predicted, there was a significant main effect of task, $F(1, 23) = 76.50$, $p < .0001$, because responses were faster for the less complex PI task (412 ms) than for the more complex NI task (521 ms). There was also a significant main effect of interhemispheric condition, $F(2, 46) = 11.86$, $p < .0002$. Newman–Keuls pairwise comparisons indicated that responses to within trials (486 ms) were significantly slower than responses to both across (457 ms) and midline (457 ms) trials ($p < .01$), which, in turn, did not differ from each other. There was also a main effect of visual field of matching probe, $F(1, 23) = 8.64$, $p < .008$, because responses were faster for LVF trials (453 ms) than for RVF trials (480 ms). However, this main effect was modified by a significant interaction between task and visual field of matching probe, $F(1, 23) = 8.37$, $p < .0082$, which resulted because the LVF advantage was larger for the NI task (37 ms) than for the PI task (16 ms). This result is consistent with data suggesting that the NI task may be performed by a visual generation strategy that is carried out better by the right hemisphere than by the left hemisphere, as opposed to a phonetic comparison of the letters' names, which would be carried out more efficiently by left-hemisphere processing (Boles, 1992; Boles & Eveland, 1983).

There was also a significant two-way interaction between task and interhemispheric condition, $F(2, 46) = 40.50$, $p < .0001$ (see Figure 3a). Consistent with prior studies (e.g., Banich & Belger, 1990), Newman–Keuls comparisons revealed that responses to within trials (410 ms) were significantly faster ($p < .05$) than those to across trials (425 ms) for the PI task, whereas responses to across trials (489 ms) were significantly faster ($p < .01$) than those to within trials (562 ms) for the NI task. In line with these effects, a planned contrast confirmed that the interaction between task (PI, NI) and interhemispheric condition (confined to the levels of within and across) was highly significant, $F(1, 23) = 60.07$, $p < .0001$.

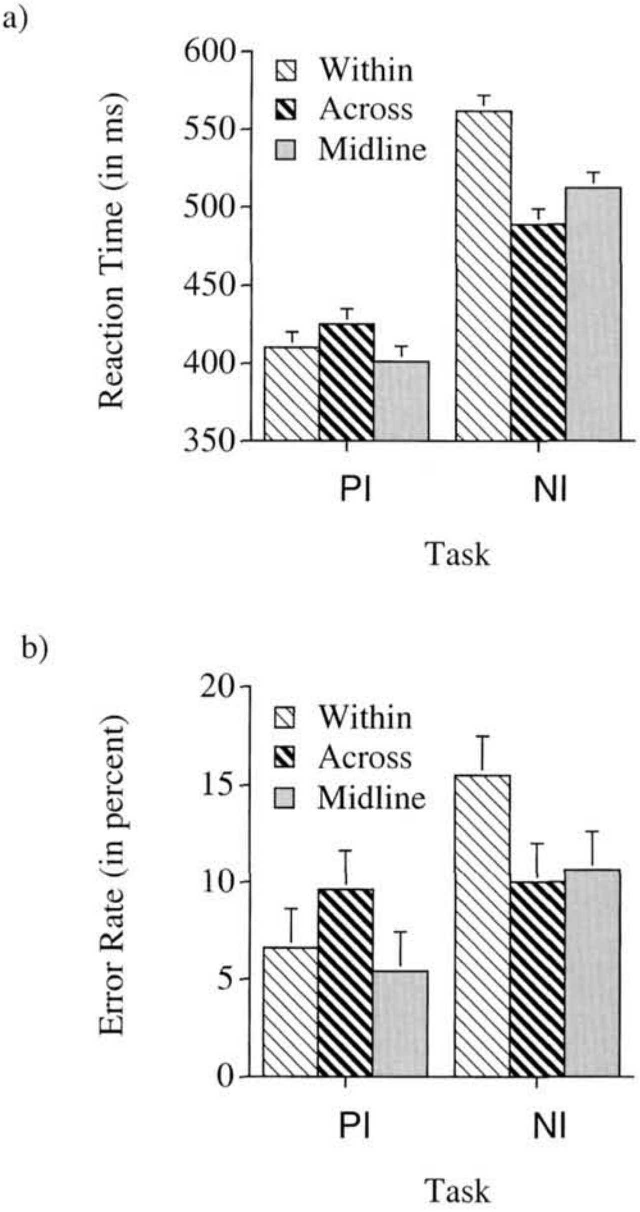

Figure 3. Performance on the physical-identity (PI) and name-identity (NI) tasks in Experiment 1 in the within, across, and midline conditions as measured by reaction time (RT; a) and error rates (b). Error bars indicate the standard error of the mean.

Also as predicted, there was a processing dissociation, indicating that the pattern of performance on midline trials was significantly different from the patterns observed on both within- and across-hemisphere trials (see Table 2). In particular, the increase in RT going from the PI to the NI task on midline trials (111 ms) was significantly smaller than that on within-hemisphere trials (152 ms), $F(1, 23) = 19.82$, $p < .0005$, but significantly larger than that on across-hemisphere trials (64 ms), $F(1, 23) = 30.18$, $p < .0001$. As predicted, an inspection of the means revealed that the intermediate pattern on midline trials occurred because performance on midline trials resembled that on within-hemisphere trials for the PI task but resembled performance on across-hemisphere trials for the NI task. Consistent with these observations, Newman–Keuls pairwise comparisons revealed that for the PI task, responses to midline trials (401 ms) did not significantly differ from those to within trials (410 ms; $p > .05$) but were significantly faster than those to across trials (425 ms; $p < .01$). For the NI task, responses to midline trials (512 ms) were significantly slower than those to across trials (489 ms; $p < .01$) but significantly faster than those to within trials (562 ms; $p < .01$). To examine whether midline RT was significantly closer to across RT than to within RT for the NI task, we calculated the RT difference between the within and midline conditions and between the midline and across conditions for each participant and entered these values into a one-way repeated measures ANOVA. This procedure confirmed that the difference between midline RT and across RT (23 ms) was significantly smaller than the difference between within RT and midline RT (50 ms), $F(1, 23) = 10.63$, $p < .004$. Furthermore, an inspection of the individual cell means revealed that for 20 of the 24 participants, RT on midline trials was closer to that on across trials than to that on within trials. Hence, as expected for the NI task, performance on midline trials

Table 2
Performance Difference Between the Name-Identity and Physical-Identity Tasks Expressed in Mean Reaction Time (in Milliseconds) and Mean Percentage Error Rates (in Parentheses) for Experiment 1

Interhemispheric condition	Name identity − physical identity
Within	
LVF	141 (5.6)
RVF	165 (12.0)
Average	153 (8.8)
Across	
pLVF	44 (0.0)
pRVF	85 (0.8)
Average	65 (0.4)
Midline	
pLVF	112 (4.8)
pRVF	110 (5.7)
Average	111 (5.3)

Note. LVF = left visual field; RVF = right visual field; p = the position of the top matching probe (e.g., pLVF means that the matching probe was in the LVF).

resembled performance on across trials more than it resembled performance on within trials. The analysis of error rate in the next section lends further support to this position.

Error rate. As observed in the RT data, there was a significant main effect of task, $F(1, 23) = 20.99, p < .0002$, because the error rate was lower for the PI task (7%) than for the NI task (12%). There was also a significant main effect of interhemispheric condition, $F(2, 46) = 7.30$, $p < .002$. Newman–Keuls comparisons indicated that the error rate was lower on midline trials (8%) than on both within (11%; $p < .01$) and across trials (10%; $p < .05$), the latter two of which did not differ from each other. We note that although this pattern differs from the RT data in which within trials were performed more slowly than across and midline trials, it does not suggest a speed–accuracy trade-off. Indeed, in no case was performance in one condition both slower and less accurate than performance in another condition. The main effect of visual field of matching probe that was significant in the RT data fell short of significance in the analysis of error rate ($p > .09$), as did the interaction between task and visual field of matching probe ($p > .052$). However, in each case, the data followed the same pattern that was observed in the analysis of mean RT.

As expected, there was a significant interaction between task and interhemispheric condition, $F(2, 46) = 13.93, p < .0001$ (see Figure 3b). Similar to the RT data, Newman–Keuls comparisons ($p < .05$) revealed that the error rate was significantly lower ($p < .05$) on within trials (7%) than on across trials (10%) for the less complex PI task but significantly higher ($p < .01$) on within trials (16%) than on across trials (10%) for the more complex NI task. Also, consistent with the RT data, the interaction between task and interhemispheric condition (when limited to the levels of within and across) was highly significant, $F(1, 23) = 22.06$, $p < .0001$.

Finally, as predicted there was a processing dissociation, indicating that the pattern of performance on midline trials was significantly different from the patterns observed on both within- and across-hemisphere trials (see Table 2). In particular, the increase in error rate going from the PI to the NI task on midline trials (5%) was significantly smaller than that on within-hemisphere trials (9%), $F(1, 23) = 5.20, p < .04$, but significantly larger than that on across-hemisphere trials (0%), $F(1, 23) = 11.81, p < .005$. As with the RT data, further analysis revealed that the distinct and intermediate pattern on midline trials occurred because performance on midline trials resembled that on within-hemisphere trials for the PI task but resembled that on across-hemisphere trials for the NI task. Newman–Keuls comparisons revealed that for the PI task, the error rate on within trials (7%) did not differ significantly ($p > .05$) from that on midline trials (5%), whereas the error rate on across trials (10%) was significantly higher than that on within ($p < .05$) and midline ($p < .01$) trials. Hence, as observed in the RT data for the PI task, performance on midline trials resembled that on within trials and differed significantly from that on across trials. For the NI task, the error rate was significantly higher on within trials (16%) than on either midline (11%) or across (10%) trials ($p < .01$ in each case), which, in turn, did not significantly differ from each other. Hence, as predicted for the NI task, performance on midline trials did not differ significantly from that on across trials and differed significantly from that on within trials.

Discussion

The data from Experiment 1 support our hypothesis that the degree to which interhemispheric cooperation underlies performance varies as a function of task complexity. First, as predicted, the pattern of performance on midline trials across the two tasks was distinct from that on within- and across-hemisphere trials. This difference occurred because the processing mode that subserved performance on midline trials appeared to change with task complexity, as predicted. For the relatively simple PI task, mean RT and error rates on midline trials did not differ significantly from those observed on within-hemisphere trials, and responses on both of these trial types were faster and more accurate than were responses on across-hemisphere trials. For the more complex NI task, the picture was less clear-cut but still consistent with our hypothesis. As predicted, mean error rates on across-hemisphere and midline trials did not differ from one another, and both were lower than on within-hemisphere trials. Although we would have predicted a similar pattern for RT, response times in the midline condition were intermediate to response times in the within- and across-hemisphere conditions. Nonetheless, an examination of the data indicated that RT on midline trials was more similar to RT on across-hemisphere trials than to RT on within-hemisphere trials. The data from Experiment 1 are therefore consistent with our hypothesis that when within- and across-hemisphere processing are equally possible, the mode that underlies performance will vary with the complexity of the task that is being performed.

Experiment 2

In Experiment 2, we attempted to replicate the pattern of interhemispheric effects observed in Experiment 1 using a display in which acuity for the bottom target item is more closely equated on within-hemisphere, across-hemisphere, and midline trials. In Experiment 1, acuity for the bottom target item was probably slightly greater on midline trials than on within- and across-hemisphere trials because even though it was positioned at the same vertical coordinate, the bottom target item on midline trials was not horizontally displaced from midline as it was on within- and across-hemisphere trials. To more closely equate acuity for the target item on midline as compared with within- and across-hemisphere trials, we modified the stimulus array used in Experiment 1 by moving the bottom target item on midline trials slightly farther beneath fixation. We hypothesized that performance on midline trials would still resemble performance on within-hemisphere trials for the less complex PI task and performance on across-hemisphere trials for the more complex NI task.

We also took the opportunity to investigate the particular stage of processing at which interhemispheric interaction modulates performance for the PI and NI tasks. Copeland and Zaidel (1996) found that a patient with an anterior callosal section did not exhibit an across-hemisphere advantage for the NI task. Because the anterior section of the corpus callosum connects mainly frontal areas, their finding suggests that interhemispheric interaction can modulate the performance of letter matching tasks at processing stages typically localized to frontal regions (e.g., response selection). This possibility is consistent with other results indicating that interhemispheric interaction modulates both response facilitation and response interference in selective attention paradigms (Banich & Passarotti, 1999; Shenker & Banich, 1999; Weissman & Banich, 1999). In Experiment 2, we therefore sought converging evidence for the view that interhemispheric interaction modulates the performance of letter matching tasks at stages beyond early perceptual processing. To do so, we used a manipulation of stimulus contrast that affects early perceptual processing areas (e.g., V1, V2) that are connected by the splenium, or posterior region of the corpus callosum. We reasoned that if interhemispheric interaction modulates the performance of letter-matching tasks by allowing a division of processing by anterior rather than posterior sections of the corpus callosum, then interhemispheric interaction should not modulate the effects of stimulus contrast on performance.

Method

Participants. Twenty-four right-handed University of Illinois students (12 men, 12 women) with normal or corrected-to-normal vision were paid $5 or received course credit for participating in the experiment. None had participated in Experiment 1.

Stimuli. The same letters used in Experiment 1 were used in Experiment 2. However, rather than presenting black letters on a white background, we presented white letters on a black background. The displays were therefore the inverse of those used in Experiment 1. Furthermore, we varied the letters' luminance and, hence, the contrast of the white letters against the constant black background. The contrast of the letters used in the high- and low-contrast conditions was determined with a photometer that measured the luminance of a full screen that was set to the same luminance as the individual letters. The luminance of the high-contrast letters was 70.58 cd/m^2 whereas that of the low-contrast letters was 6.17 cd/m^2. The luminance of the background was 3.87 cd/m^2. Hence, the contrast for the high-contrast letters (0.896) was almost four times greater than the contrast for the low-contrast letters (0.229). Half the trials consisted of three low-contrast letters and half consisted of three high-contrast letters. High- and low-contrast letters were randomly intermixed in the same trial blocks.

Table 3

Mean Reaction Time (in Milliseconds) and Mean Percentage Error Rates (in Parentheses) for Experiment 2

Interhemispheric condition	Task: Physical identity	Task: Name identity
Within		
LVF	446 (6.1)	590 (12.2)
RVF	476 (6.2)	646 (15.8)
Average	461 (6.2)	618 (14.0)
Across		
pLVF	481 (7.7)	543 (10.3)
pRVF	486 (7.3)	598 (10.4)
Average	483 (7.5)	571 (10.3)
Midline		
pLVF	462 (2.9)	544 (7.0)
pRVF	483 (5.5)	608 (11.6)
Average	472 (4.2)	576 (9.3)

Note. LVF = left visual field; RVF = right visual field; p = the position of the top matching probe (e.g., pLVF means that the topmatching probe was in the LVF).

The bottom target item on midline trials was presented 2.2° beneath fixation (rather than 2.0°, as in Experiment 1) to more closely equate acuity in the midline condition to that in the within- and across-hemisphere conditions (see Rovamo & Virsu, 1979, for a method by which to calculate acuity in various parts of the visual field).[3] All other aspects of the stimuli were equivalent to the stimuli used in Experiment 1.

Procedure. The procedure was identical to that used in Experiment 1.

Results

We performed separate repeated measures ANOVAs on average RTs for correct match trials and average error rates for match trials with the following within-participants variables: task (PI, NI), letter contrast (high, low), interhemispheric condition (within, across, midline) and visual field of matching probe (LVF, RVF). Average RTs and error rates for the main conditions of Experiment 2 are reported in Table 3.

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[3] Prior to Experiment 2, we conducted a small pilot study to determine where on the midline a target letter needed to be placed to be discriminated equally rapidly as targets positioned in either the LVF or the RVF. We found that placing a letter 2.2° directly beneath fixation led to equivalent RTs for discriminating midline as compared with lateralized targets. This procedure was used so that interpretations of RT relations between midline and within- and across-hemisphere trials could be made less ambiguously in Experiment 2 than in Experiment 1.

RT. There were four significant main effects. As predicted, there was a significant main effect of task, $F(1, 23) = 95.51$, $p < .0001$, because responses were significantly faster for the less complex PI task (472 ms) than for the more complex NI task (588 ms). There was also a significant main effect of interhemispheric condition, $F(2, 46) = 3.57$, $p < .04$. Newman–Keuls pairwise comparisons ($p < .05$) indicated that responses to within trials (540 ms) were significantly slower than responses to both across (527 ms) and midline (524 ms) trials, which, in turn, did not differ from one another. The main effect of letter contrast was also significant, $F(1, 23) = 57.34$, $p < .0001$, because, as expected, responses were faster to high-contrast letters (510 ms) than to low-contrast letters (550 ms). Finally, there was a significant main effect of visual field of matching probe, $F(1, 23) = 15.57$, $p < .0007$, because responses were faster to LVF trials (511 ms) than to RVF trials (549 ms).

Four significant interactions qualified the main effects. First, there was a significant interaction between task and interhemispheric condition, $F(2, 46) = 22.09$, $p < .0001$ (see Figure 4a). As in Experiment 1, Newman–Keuls comparisons revealed that responses were significantly faster ($p < .05$) to within trials (461 ms) than to across trials (483 ms) for the PI task but significantly faster ($p < .01$) to across trials (571 ms) than to within trials (618 ms) for the NI task. Consistent with these findings, a planned contrast revealed a highly significant interaction between task (PI, NI) and interhemispheric condition (when confined to the levels of within and across), $F(1, 23) = 28.09$, $p < .0001$.

Of most importance to the present hypothesis, there was a processing dissociation, indicating that the pattern of performance on midline trials was significantly different from the patterns observed on both within- and across-hemisphere trials (see Table 4). As in Experiment 1, the increase in RT going from the PI to the NI task on midline trials (104 ms) was significantly smaller than that on within-hemisphere trials (157 ms), $F(1, 23) = 23.21$, $p < .0001$, but significantly larger than that on across-hemisphere trials (88 ms), $F(1, 23) = 4.14$, $p < .054$. Newman–Keuls comparisons indicated that responses to midline trials (472 ms) did not differ significantly from responses to within trials (461 ms; $p > .05$) or across trials (483 ms; $p > .05$) for the PI task. Thus, it is difficult (using only the RT data) to determine which mode of processing subserved performance in the midline condition for the PI task. However, the error rate data presented in the next section help to clarify this issue and suggest that within-hemisphere processing did in fact underlie performance on midline trials for the PI task.

The data for the NI task were much easier to interpret. Responses to midline trials (576 ms) did not significantly differ from responses to across trials (571 ms; $p > .05$), whereas responses in both of these conditions were significantly faster ($p < .01$) than responses to within trials (618 ms). Hence, as predicted for the NI task, performance in the midline condition was equivalent to that in the across condition and differed significantly from that in the within condition.

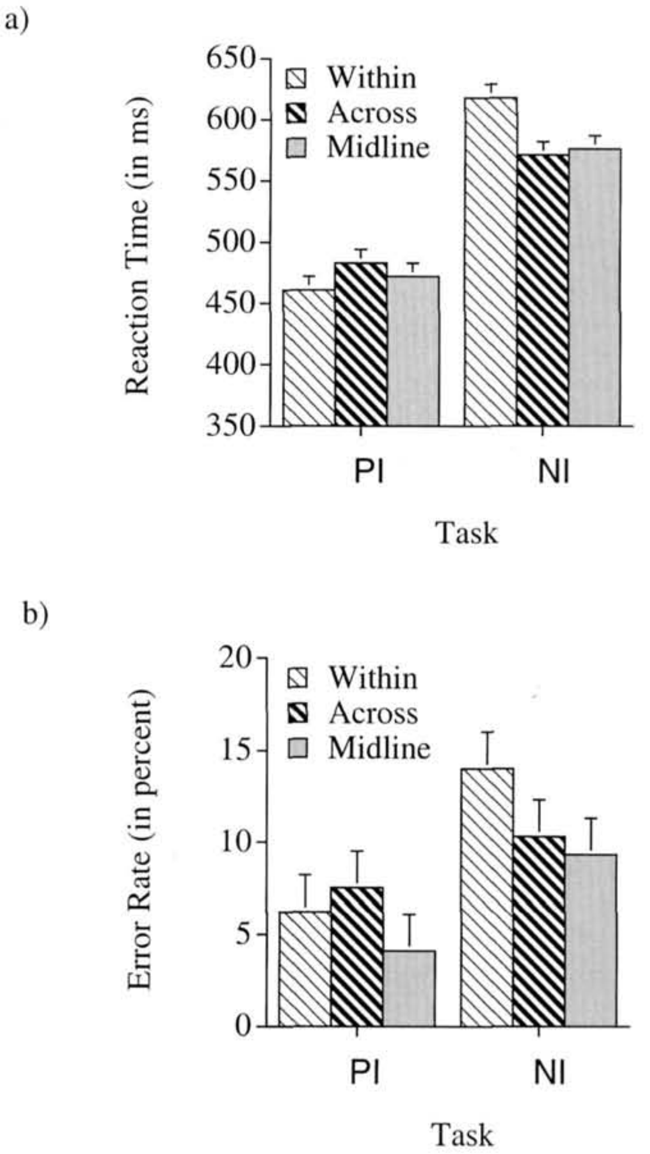

Figure 4. Performance on the physical-identity (PI) and name-identity (NI) tasks in Experiment 2 in the within-hemisphere, across-hemisphere, and midline conditions as measured by reaction time (RT; a) and error rate (b). Error bars indicate the standard error of the mean.

Second, there was a significant interaction between task and letter contrast, $F(1, 23) = 4.77$, $p < .04$, because using low-contrast as compared with high-contrast stimuli slowed responses more for the NI task (50 ms) than for the PI task (30 ms). This finding is consistent with prior suggestions that participants may perform the NI task by way of a case-transformation strategy (e.g., Boles, 1992; Boles & Eveland, 1983; Posner, 1969). For example, in the model of the NI task proposed by Boles and colleagues, participants begin by generating a visual representation of the opposite-case version of one or more letters in the display. These visual representations are then compared with the original stimuli. For example, for the letter pair *Aa*, an *a* might be generated from the *A* or an *A* might be generated from the *a*. Then, the generated images would be compared with the

Table 4

Performance Difference Between the Name-Identity and Physical-Identity Tasks Expressed in Mean Reaction Time (in Milliseconds) and Mean Percentage Error Rates (in Parentheses) for Experiment 2

Interhemispheric condition	Name identity – physical identity
Within	
LVF	144 (6.1)
RVF	170 (9.6)
Average	157 (7.8)
Across	
pLVF	62 (2.6)
pRVF	112 (3.1)
Average	87 (2.8)
Midline	
pLVF	82 (4.1)
pRVF	125 (6.1)
Average	103 (5.1)

Note. LVF = left visual field; RVF = right visual field; p = the position of the top matching probe (e.g., pLVF means that the matching probe was in the LVF).

original stimulus representations (i.e., *A* to *A* or *a* to *a*), and, if a match was detected, a match decision would be reached. In this model of the NI task, a degradation of the stimulus could lead to impoverished input for two processes further downstream—both the generation and the comparison process (i.e., poor sensory input could lead to an inferior stimulus representation, which could lead to impaired generation, which could lead to an impaired comparison). For the PI task, there is a comparison but no generation process. Hence, stimulus degradation would affect only one process—the comparison process. According to this analysis, one might expect stimulus degradation to affect the NI more than the PI task, as we found.

Third, there was a significant interaction between task and visual field of matching probe, $F(1, 23) = 14.08, p < .002$, because, as observed in Experiment 1, the LVF advantage was larger for the NI task (58 ms) than for the PI task (18 ms). Finally, there was a significant interaction between letter contrast, interhemispheric condition, and visual field of matching probe, $F(2, 46) = 4.38, p < .02$. This three-way interaction resulted because using high-contrast as compared with low-contrast stimuli increased the size of the LVF advantage more for midline trials than for both within trials, $F(1, 23) = 8.14, p < .01$, and across trials, $F(1, 23) = 5.99$, $p < .03$.

Of importance to the issue of determining whether interhemispheric interaction modulates the performance of the PI and NI tasks at early stages of perceptual processing, the interaction between letter contrast, interhemispheric condition, and task did not approach significance ($F < 1$). Planned contrasts revealed that varying the contrast of the letters did not modulate the size of the across-hemisphere advantage for the PI task ($F < 1$) or for the NI task ($F < 1$). This finding is consistent with the view that interhemispheric interaction does not modulate the performance of the PI and NI tasks at early stages of perceptual processing.

Error rate. As observed in the RT data, there was a significant main effect of task, $F(1, 23) = 9.62, p < .006$, because the error rate was lower for the PI task (6%) than for the NI task (11%). There was also a significant main effect of interhemispheric condition, $F(2, 46) = 8.07, p < .002$. Newman–Keuls comparisons indicated that the error rate was significantly lower on midline trials (7%) than on both within (10%; $p < .01$) and across trials (9%; $p < .05$), which, in turn, did not differ significantly from each other. The main effect of visual field of matching probe that was significant in the RT data fell short of significance in the analysis of error rate ($p > .08$), as did the interaction between task and visual field of matching probe ($p > .16$).

As in Experiment 1, there was also a significant interaction between task and interhemispheric condition, $F(2, 46) = 4.26, p < .03$ (see Figure 4b). Newman–Keuls comparisons revealed that the error rate on within trials (6%) did not significantly differ from that on across trials (8%) for the less complex PI task, whereas the error rate on within trials (14%) was significantly higher ($p < .01$) than that on across trials (10%) for the NI task. Consistent with these effects, a planned contrast revealed a significant interaction between task (PI, NI) and interhemispheric condition (when limited to the levels of within and across), $F(1, 23) = 8.24$, $p < .009$. Hence, as predicted, across-hemisphere processing was more advantageous to performance for the NI task than for the PI task.

As predicted, the increase in error rate going from the PI to the NI task on midline trials (5%) was smaller than that on within-hemisphere trials (8%), $F(1, 23) = 2.48, p < .13$, and larger than that on across-hemisphere trials (3%), $F(1, 23) = 1.86$, $p < .19$ (see Table 4). These effects fell short of significance in the analysis of error rates, however. Nevertheless, for the PI task, Newman–Keuls comparisons revealed that the error rate on midline trials (4%) did not differ significantly from that on within trials (6%) but was significantly lower ($p < .05$) than that on across trials (8%), as predicted. Also as hypothesized, for the NI task, the error rate on midline trials (9%) was not significantly different from that on across trials (10%) but was significantly lower than that on within trials (14%; $p < .01$). Hence, as predicted, performance in the midline condition resembled whichever processing mode (within- or across-hemisphere) was most efficient for the task being performed.

Finally, there was a significant interaction between interhemispheric condition and visual field of matching probe, $F(2, 46) = 3.36, p < .05$, that was relatively unimportant with regard to our hypothesis. This interaction occurred because the right-hemisphere advantage was largest on midline trials (4%), smaller on within trials (2%), and smallest on across trials (0%).

Of importance to the issue of whether interhemispheric interaction modulates performance at early stages of perceptual processing, the three-way interaction between task, letter contrast, and interhemispheric condition was not significant ($F < 1$), as was the case in the analysis of mean RT. Planned contrasts revealed that the across-hemisphere advantage (relative to within-hemisphere processing) was not affected by the manipulation of letter contrast for the PI task, $F(1, 23) = 1.33, p > .25$, or for the NI task ($F < 1$).

Discussion

As in Experiment 1, the pattern of performance on midline trials was distinct from that on both within- and across-hemisphere trials (although the processing dissociation was only significant for the RT data). Furthermore, this distinct pattern appears to have occurred because the processing mode that underlies performance in the midline condition tends to be whichever mode (i.e., within- or across-hemisphere) is most efficient for the task currently being performed. Although, for the PI task, RTs to midline trials were midway between those to within- and across-hemisphere trials (and did not significantly differ from either), the error rate on midline trials did not significantly differ from that on within-hemisphere trials and was significantly lower than that observed on across-hemisphere trials. Therefore, the error rate data suggest that performance on midline trials was subserved by within-hemisphere processing for the PI task. For the NI task, both RT and percentage correct in the midline condition did not significantly differ from these measures in the across-hemisphere condition but did significantly differ from these measures in the within-hemisphere condition. Hence, as predicted for the more complex NI task, performance in the midline condition appeared to be subserved by across-hemisphere processing.

We observed the same pattern of effects across Experiments 1 and 2, despite the fact that we varied the acuity of the midline item. In Experiment 1, the acuity of the bottom target item was likely greater in the midline condition than in the within- and across-hemisphere conditions. In contrast, in Experiment 2, the acuity of the bottom target item was more closely matched for all three conditions. Nevertheless, we found in both experiments that the pattern of performance on midline trials was distinct from that on within- and across-hemisphere trials. In particular, performance on midline trials was more similar to that on within-hemisphere trials for the PI task but more similar to that on across-hemisphere trials for the NI task. This effect is therefore unlikely to be due to subtle differences in acuity between the midline and within- and across-hemisphere conditions.

Our present findings also suggest that interhemispheric interaction does not modulate the performance of letter-matching tasks at early stages of perceptual processing. Specifically, we found that interhemispheric interaction does not modulate performance differentially as a function of stimulus contrast, either for the PI or for the NI task. This result is consistent with evidence that interhemispheric interaction modulates letter-matching performance at stages beyond early perceptual processing by way of communication across the anterior section of the corpus callosum (Copeland & Zaidel, 1997).

An anonymous reviewer noted that when stimuli are degraded (e.g., low-contrast stimuli), imagery processes may be used to aid identification processes (Kosslyn, 1994) or greater amounts of attention may be allocated to performance because spatial attention has recently been found to increase contrast sensitivity (Yeshurun & Carrasco, 1998). We cannot, in the present study, evaluate whether or not such processes were actually evoked by our low-contrast stimuli. If they were evoked, then our finding suggests that not all processes are facilitated by a division between the hemispheres. Clearly, future studies are needed to determine whether there are some cognitive and neural loci at which a hemispheric division of labor modulates performance and others at which it does not.

Our finding that interhemispheric interaction does not modulate the effects of varying stimulus contrast also illustrates that the across-hemisphere advantage is not simply generated by task difficulty (as measured by overall RT). Increasing task difficulty by using low- as compared with high-contrast letters significantly increased mean RT but did not affect the efficiency of across-hemisphere processing relative to that of within-hemisphere processing. This result suggests that the across-hemisphere advantage is driven by a division of operations at particular stages of processing rather than by overall RT. One might object that overall RT was raised by only 40 ms in the stimulus contrast manipulation as compared with 118 ms in the manipulation of task (i.e., PI vs. NI). Because the efficiency of interhemispheric interaction was affected by varying task but not by varying stimulus contrast, it could be argued that overall task difficulty is still what determines the efficiency of across-hemisphere processing relative to that of within-hemisphere processing. We consider this explanation unlikely, however, because in another of our studies (Banich & Passarotti, 1999), a manipulation of selective attention that increased RT by roughly 40 ms did increase the relative efficiency of across-hemisphere processing. Given that we did not observe a similar increase in the efficiency of across-hemisphere processing when we used low- compared with high-contrast letters, we conclude that the ability to divide processing at particular stages plays a greater role than overall task difficulty (as indexed by mean RT) in determining the size of the across-hemisphere advantage.

Experiment 3

In Experiment 3, we took a different approach to examining our hypothesis that the processing mode (i.e., within- or across-hemisphere) that is most efficient for a task is the one that underlies performance when both modes are possible. Unlike in Experiments 1 and 2, in this experiment, we measured performance across three levels of computational complexity, all of which produced an across-hemisphere advantage to varying degrees. This approach allows for a more fine-grained analysis of performance on trials in which within- and across-hemisphere processing are equally possible. If such trials are processed by the optimal across-hemisphere mechanism, then the pattern of performance across the different levels of computational complexity for these trials should mimic the pattern observed on across-hemisphere trials.

To investigate this issue, we had participants perform a five-item categorical-identity task in which they indicated whether the bottom target item (which appeared either in the

LVF or the RVF) came from the same category (letters, numbers, or symbols) as any of four top probe items (two probes appeared in the LVF and two appeared in the RVF). On match trials, two of the probes came from the same category as the bottom target item. As in Experiments 1 and 2, task performance was measured in three conditions. The matching probes could appear in the same visual field as the target item (the within-hemisphere condition), in the opposite visual field as the target item (the across-hemisphere condition), or divided such that one probe was in the same visual field as the target while the other was in the opposite visual field (the divided condition; see Figure 5). It is important to notice that the divided trials here are akin to the midline trials in the prior experiments in that they allow the match decision to be made through either within- or across-hemisphere processing. Because each hemisphere receives a matching probe, the decision may be made by comparing the target with the within-hemisphere probe or by comparing the target with the across-hemisphere probe. It is also important to notice that in this experiment, unlike Experiments 1 and 2, the positions in which stimuli appear do not vary across the three trial types. Therefore, differences in performance between the divided and other conditions cannot arise from differences in acuity for the stimuli on these trial types.

Also, as in Experiments 1 and 2, we measured performance in each of our three conditions above as we varied the levels of a second variable. Specifically, we used three conditions in which we varied the temporal onset of the target and probe items while keeping constant the nature of the decision to be made. We chose to vary the temporal presentation of the target and probe items because prior studies have demonstrated that the across-hemisphere advantage for a given task is greater when the target and probe items appear simultaneously than when they appear sequentially (Banich, 1985; Hellige, 1987). This effect presumably occurs because sequential presentation reduces the number of computations that must simultaneously be performed and, hence, reduces the advantage afforded by across-hemisphere processing. In the relatively complex simultaneous condition, the probes and the target were presented simultaneously. In the less complex partially overlapping condition, the presentation of the probes and the target overlapped partially but not completely. In the relatively simple sequential presentation condition, the target was presented after the four probes.

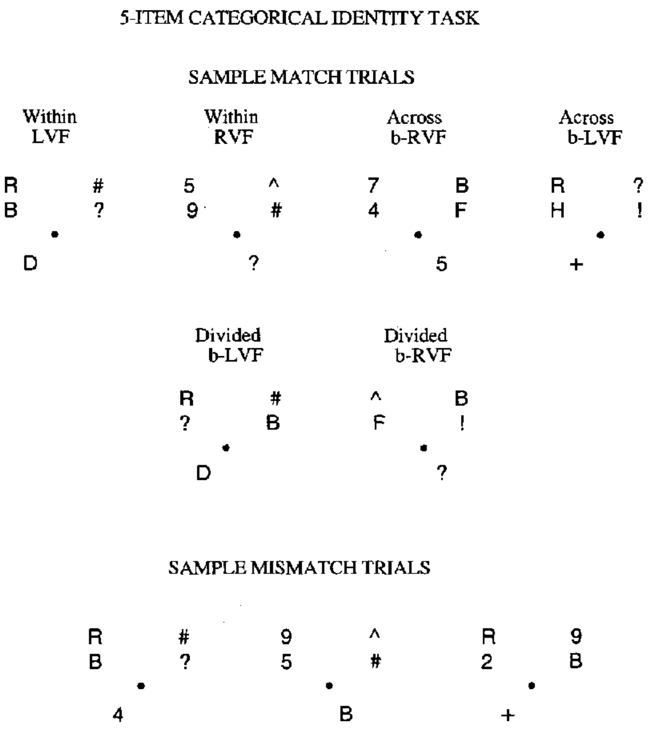

Figure 5. Sample match and mismatch trials for the categorical-identity task used in Experiment 3. Participants were asked to decide whether the bottom target item came from the same category (letters, numbers, or symbols) as one of the top four probe items. LVF = left visual field; RVF = right visual field; b = position of the bottom target item.

We made three predictions. First, because we used a categorical-identity task (similar to the NI task in that it requires the items to be processed both perceptually and categorically), we predicted that we would observe an across-hemisphere advantage for all the presentation conditions. Second, we predicted that there would be a larger across-hemisphere advantage for the more complex simultaneous presentation condition than for the less complex partially overlapping and sequential presentation conditions. In other words, we predicted that the increase in RT going from the partially overlapping to the simultaneous presentation condition would be smaller on across-hemisphere trials than on within-hemisphere trials. Third, we predicted that across-hemisphere processing would underlie performance on divided trials. This prediction is derived from our hypothesis that when within- and across-hemisphere processing are equally possible, the most efficient mode will underlie performance.

Because there were two possible match decisions in each trial in Experiment 3 (rather than one, as in Experiments 1 and 2), we expected that our ability to meaningfully compare absolute levels of performance in the within-hemisphere, across-hemisphere, and divided conditions would be limited. In particular, we expected that performance on divided trials might be slower than that on across-hemisphere trials, even if it was driven by across-hemisphere processing as predicted. We reasoned that this result might occur because on divided trials, only one of the two possible match decisions has access to the relatively fast across-hemisphere process. In contrast, on across-hemisphere trials, both of the possible match decisions have access to the relatively efficient across-hemisphere process. Because we expected absolute levels of performance on divided trials to be difficult to compare with those on within- and across-hemisphere trials, the test of our hypothesis in Experiment 3 relied heavily on processing dissociations (i.e., patterns of performance across the levels of task complexity in the divided, within-hemisphere, and across-hemisphere conditions). We predicted that if across-hemisphere processing underlies performance on divided trials, then the increases in RT going from (a) the sequential to the partially overlapping condition and (b) the partially overlapping to the simultaneous presentation condition, should be more similar on divided and across-hemisphere trials than on divided and within-hemisphere trials.

Method

Participants. Twenty-four right-handed University of Illinois students (12 men, 12 women) with normal or corrected-to-normal vision were paid $5 or received course credit for participating in the experiment.

Stimuli. The stimuli were six capital letters (*B, D, F, G, H, R*), six digits (1, 2, 4, 5, 7, 9), and six symbols (!, #, ?, /\, +, π). The capital letters were displayed in Geneva 41-point font, but the digits and symbols were presented in Geneva 40-point font to make them appear equivalent to the letters in terms of size and discriminability. The pi sign was modified using Adobe Photoshop 2.0 (Adobe Systems, Inc., San Jose, CA) so that it would be made of straight lines and hence appear to be in the same font as the other stimuli. All stimuli subtended a maximum of 1° of visual angle horizontally and vertically. In each trial, five stimuli were presented. The target item was centered 2° beneath fixation, either 2° to the left or 2° to the right. Two of the four probe items were centered 1° above fixation, one centered 2° to the left and the second centered 2° to the right. The remaining two probe items were centered 3° above fixation, one centered 2° to the left and the other centered 2° to the right. All stimuli were displayed as black letters on a white background. A Macintosh Centris 650 equipped with a 14-in. (35.6-cm) color monitor and SuperLab software was used to present the stimuli and to collect responses.

Procedure. The preexperiment screening for visual problems and handedness questionnaire were identical to those administered in Experiments 1 and 2. Following these screening procedures, participants were instructed to decide on each trial whether the bottom item in the display came from the same category (letters, numbers, or symbols) as any of the top items. The category to which each stimulus item belonged was made explicit to each participant at the beginning of the experiment.

On each trial, participants viewed a fixation dot for 500 ms and then saw the stimulus array for 200 ms. Participants were asked to use their index finger to press one computer key if the target came from the same category as any of the probes (50% of trials) and their middle finger from the same hand to press another key if the target did not come from the same category as any of the four probes (50% of trials). As in Experiments 1 and 2, hand was counterbalanced within participants and response key-decision mappings were counterbalanced across participants.

On all match trials, two of the four probes matched the target. On within-hemisphere match trials, no interhemispheric interaction was required because both matching probes appeared in the same visual field as the target, either both in the left visual field (within-LVF trials) or both in the right visual field (within-RVF trials). On across-hemisphere match trials, interhemispheric interaction was required to reach a match decision because both matching probes appeared in the visual field opposite to the target, either with the bottom target in the RVF and both matching probes in the LVF (across-bRVF trials) or with the bottom target in the LVF and both matching probes in the RVF (across-bLVF trials). On divided trials, within- and across-hemisphere processing were equally possible because one of the matching probes was presented in the same visual field as the target (e.g., the LVF) while the other was presented in the opposite visual field (e.g., the RVF). As on within- and across-hemisphere trials, one of the matching items was placed in the upper row of probes, whereas the other was placed in the lower row. Thus, there were divided-bLVF trials, in which the bottom target item appeared in the LVF, and divided-bRVF trials, in which the bottom target item appeared in the RVF. The different trial types—within LVF, within RVF, across bLVF, across bRVF, divided bLVF, and divided bRVF—appeared equally often in match trials.

On mismatch trials, two probes came from one category (e.g., symbols) and two came from another (e.g., digits), as on match trials, but the target item came from a third category (e.g., letters). Hence, no distinction between the within- and across-hemisphere trial types was possible for mismatch trials. As in Experiments 1 and 2, each stimulus appeared in each possible location an equal number of times on match and mismatch trials to preclude a response bias from developing on the basis of an item's position in the display.

The task was performed in three conditions that differed with respect to the time delay between the presentation of the top probe items and the presentation of the bottom target item (see Figure 6). In all three conditions, each letter, symbol, or digit appeared for 100

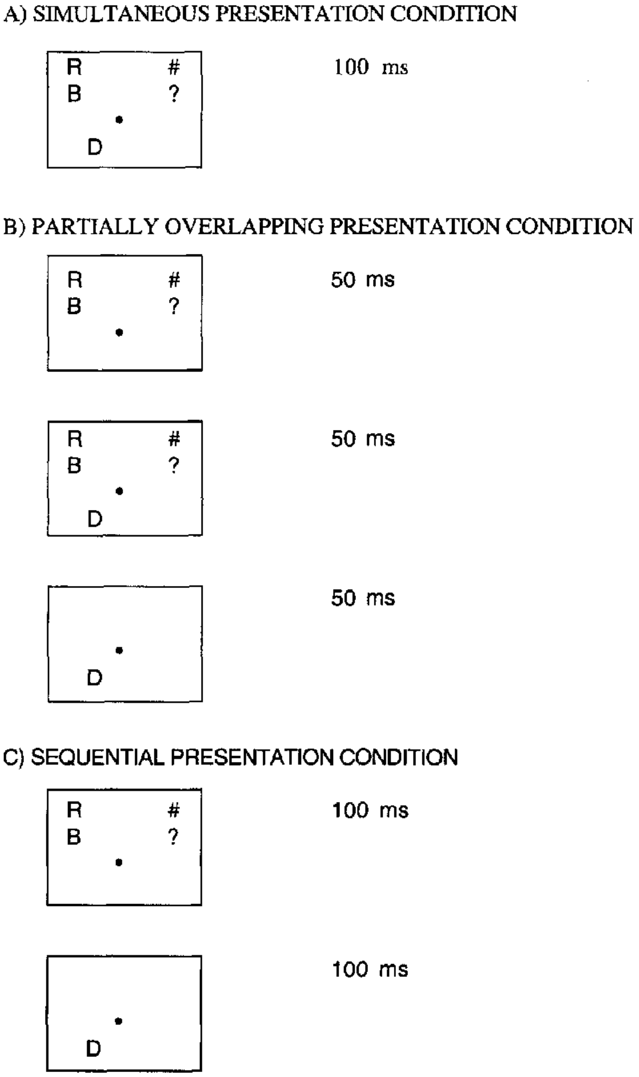

Figure 6. The sequence of events for a trial in the simultaneous (A), partially overlapping (B), and sequential presentation (C) conditions.

ms. In the simultaneous presentation condition, all five stimuli appeared simultaneously for 100 ms. The partially overlapping presentation condition was divided into three time intervals. For the first 50 ms, only the four probe items appeared. For the next 50 ms, the target and all four probes appeared. For the last 50 ms, only the target was displayed. The sequential presentation condition was divided into two time intervals. For the first 100 ms, only the four probes appeared. For the next 100 ms, only the target was displayed. It is important to notice that in all displays, each of the items appeared for 100 ms, and what varied was whether the presentation was simultaneous, partially overlapping, or sequential. The three conditions were blocked, and the order in which they were administered was counterbalanced across participants. There were 38 practice trials and 216 test trials for each of the interstimulus interval conditions.

Results

We performed separate repeated measures ANOVAs on average RTs for correct match trials and average error rates for match trials with the following within-participants variables: presentation condition (simultaneous, partially overlapping, sequential), interhemispheric condition (within, across, divided) and visual field of bottom item (LVF, RVF).[4,5] Because of the difficulty of the task, only RTs greater than 3,000 ms were treated as errors. Average RTs and mean error rates for Experiment 3 are reported in Table 5.

RT. There was a marginally significant main effect of presentation condition, $F(2, 46) = 3.12$, $p < .06$. As predicted, RT was longer in the simultaneous condition (701 ms) than in the partially overlapping (643 ms) and sequential (655 ms) conditions, but Newman–Keuls pairwise comparisons revealed no significant differences among the means ($p > .05$ in all cases). There was also a significant main effect of interhemispheric condition, $F(2, 46) = 6.84$, $p < .003$. Newman–Keuls comparisons ($p < .01$) revealed that responses were faster to across trials (648 ms) than to within (678 ms) and divided (674 ms) trials.

As predicted, there was also a significant interaction between presentation condition and interhemispheric condition, $F(4, 92) = 2.55$, $p < .05$. Tests of simple effects revealed that there was a significant effect of presentation condition on within trials, $F(2, 46) = 4.87$, $p < .02$, but not on across or divided trials ($p > .10$ in both cases), which explains why the main effect of presentation condition above was only marginally significant. Further tests revealed that there was a significant simple effect of interhemispheric condition for the simultaneous, $F(2, 46) = 7.82$, $p < .002$, and partially overlapping, $F(2, 46) = 4.02$, $p < .02$, conditions, but not for the sequential condition ($p > .10$; see Table 6 for pairwise comparisons within each of these conditions).

Table 5
Mean Reaction Time (in Milliseconds) and Mean Percentage Error Rates (in Parentheses) in Experiment 3

Interhemispheric condition	Task Sequential	 Partially overlapping	 Simultaneous
Within			
LVF	637 (5.3)	637 (6.0)	710 (5.6)
RVF	680 (10.7)	659 (6.5)	744 (5.3)
Average	658 (8.0)	648 (6.3)	727 (5.4)
Across			
bLVF	664 (6.0)	659 (4.2)	720 (5.1)
bRVF	618 (2.1)	596 (6.7)	634 (3.5)
Average	641 (4.1)	627 (5.4)	677 (4.3)
Divided			
bLVF	675 (5.3)	654 (5.6)	714 (5.6)
bRVF	659 (6.5)	653 (5.1)	689 (5.3)
Average	667 (5.9)	653 (5.3)	701 (5.4)

Note. LVF = left visual field; RVF = right visual field; b = the position of the bottom target item (e.g., bLVF means that the target item was in the LVF).

Table 6
Differences in Reaction Time (in Milliseconds) Between the Divided, Within-, and Across-Hemisphere Conditions as a Function of Presentation Condition in Experiment 3

Reaction time difference	Presentation condition Sequential	 Partially overlapping	 Simultaneous
Within − across	17	21	50*
Divided − within	9	5	−26*
Divided − across	26	26*	24*

*$p < .05$.

Of most importance to our hypothesis, however, are the patterns of performance on within, across, and divided trials. As can be seen in Table 7, response times in the within, across, and divided conditions did not change relative to one another going from the sequential to the partially overlapping presentation condition ($F < 1$ in each possible case). This observation is consistent with Banich's (1985) finding that a delay between the presentation of the target and probe items produced the same reduction of the across-hemisphere advantage (relative to a condition in which the target and probes were presented simultaneously), regardless of whether it was 50 ms or 250 ms long. It does not allow us to determine, though, which processing mode subserved performance on divided trials.

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[4] As in Experiments 1 and 2, RT was measured from stimulus offset to response. One may question this procedure because it does not capture the fact that stimulus presentation time varied in the three interstimulus interval conditions. However, it equates the three conditions with respect to the amount of time taken to reach a decision once all the items have been displayed.

[5] For the divided trials in Experiment 3, there is one matching probe in the LVF and another matching probe in the RVF. Therefore, we distinguish between the two types of divided trials by referring to the visual field of the bottom target item (i.e., divided-bLVF and divided-bRVF trials). To maintain consistency across trial types, we also distinguish between the two types of across-hemisphere trials by referring to the visual field of the bottom target item (i.e., across-bLVF and across-bRVF trials). Although this notation differs from the designations used in Experiments 1 and 2, in which we distinguished between the two types of across-hemisphere trials by referring to the visual field of the top matching probe item (i.e., across-pLVF and across-pRVF trials), it does allow us to use a consistent terminology for all three trial types in Experiment 3.

Table 7

Differences in Reaction Time (in Milliseconds) Between the Sequential, Partially Overlapping, and Simultaneous Presentation Conditions as a Function of Interhemispheric Condition in Experiment 3

Interhemispheric condition	Task subtraction		
	SEQ − PO	SIM − SEQ	SIM − PO
Within			
LVF	0	73	73
RVF	21	64	85
Average	10	69	79
Across			
bLVF	5	56	61
bRVF	22	16	38
Average	14	36	50
Divided			
bLVF	21	39	60
bRVF	6	30	36
Average	14	34	48

Note. SEQ = sequential presentation condition; PO = partially overlapping condition; SIM = simultaneous presentation condition; LVF = left visual field; RVF = right visual field; b = the position of the bottom target item (e.g., bLVF means that the target item was in the LVF).

As predicted, however, the pattern of performance on divided trials mimicked that on across-hemisphere trials for the other conditions. First, the difference in RT between the partially overlapping and simultaneous presentation conditions was significantly larger for within trials (79 ms) than for either across trials (50 ms), $F(1, 23) = 4.57, p < .05$, or divided trials (48 ms), $F(1, 23) = 6.97, p < .02$, the latter two of which did not significantly differ ($F < 1$). It is important to notice in Table 7 that the virtually identical patterns on divided and across-hemisphere trials occurred for both bLVF and bRVF trials. Thus, as predicted, performance on divided trials paralleled across-hemisphere performance and deviated significantly from within-hemisphere performance going from the partially overlapping to the simultaneous presentation condition. Second, going from the least complex sequential presentation condition to the most complex simultaneous presentation condition, the increase in RT on divided trials (34 ms) did not differ from that on across-hemisphere trials (36 ms, $F < 1$) but was significantly different from that on within-hemisphere trials (69 ms), $F(1, 23) = 8.37, p < .01$. However, a speed–accuracy trade-off between the sequential and other presentation conditions for RVF trials limits the interpretability of this comparison (see discussion in *Error rate*).

Error rate. There was a significant main effect of interhemispheric condition, $F(2, 46) = 5.77, p < .007$. Newman–Keuls comparisons revealed that the error rate on across trials (5%) was significantly lower ($p < .01$) than that on within trials (7%) but did not differ significantly from that on divided trials (6%).

There was also a significant interaction between presentation condition, interhemispheric condition, and visual field of the bottom item, $F(4, 92) = 4.11, p < .005$. This interaction occurred because, for RVF trials only, the across-hemisphere advantage (relative to within-hemisphere processing) was unexpectedly larger in the sequential presentation condition (9%) than in the partially overlapping (0%), $F(1, 23) = 13.31, p < .002$, and simultaneous (2%), $F(1, 23) = 8.23, p < .009$, presentation conditions. Newman–Keuls comparisons indicated, however, that there were no significant differences in mean error rates between any conditions ($p > .05$ in all possible cases) except between the within-RVF trial type for the sequential presentation condition and all other cells in the design ($p < .05$ in each case). Therefore, the unexpected finding above does not affect the interpretation of the RT data from the simultaneous and partially overlapping conditions, in which the pattern of performance on divided trials mimicked that on across-hemisphere trials.

Discussion

Although we used a completely different paradigm than in Experiments 1 and 2, we obtained further support for our hypothesis in Experiment 3. As predicted, the patterns of performance for divided and across-hemisphere trials were similar to one another, and each differed from the pattern observed on within-hemisphere trials. Of importance, acuity for all the items in the display was matched on within-hemisphere, across-hemisphere, and divided trials. Hence, the effects we have observed can be taken as strong support for the view that across-hemisphere processing underlies the performance of complex tasks, even under conditions in which within- and across-hemisphere processing are equally possible.

General Discussion

The present data provide a theoretically important extension of prior findings that interhemispheric interaction aids the performance of complex tasks more than it aids the performance of simpler ones (e.g., Banich & Belger, 1990). In particular, our results generalize these findings to more naturalistic situations by demonstrating that even when within- and across-hemisphere processing are equally possible, the hemispheres couple their processing when tasks are complex but not when they are relatively simple. Because both the PI and the NI tasks can be performed equally well by the right and left hemispheres of split-brain patients (Eviatar & Zaidel, 1994), our finding that the NI task is divided across both hemispheres is likely evidence of functional rather than mandatory recruitment of both hemispheres to performance. Thus, the present results suggest that one function of interhemispheric interactions is to allow brain regions in both hemispheres to be functionally recruited to performance when tasks are relatively complex.

We obtained evidence that the hemispheres can dynamically couple and uncouple their processing from two distinct paradigms. In Experiments 1 and 2, we varied computational complexity by having participants perform a less complex PI task and a more complex NI task. Replicating prior data (e.g., Banich & Belger, 1990), we observed a within-hemisphere advantage for the PI task that shifted to an across-hemisphere advantage for the NI task. Of most importance, the pattern of performance on midline trials across the levels of task complexity was distinct from the patterns on within- and across-hemisphere trials. As predicted, the distinct pattern of performance occurred because performance on midline trials resembled that on within-hemisphere trials for the relatively simple PI task (for which there was a within-hemisphere advantage) but resembled that on across-hemisphere trials for the more complex NI task (for which there was an across-hemisphere advantage). In Experiment 3, we varied computational demands by varying the temporal onset of the target and probe items in a category matching task. We found that the pattern of performance on divided trials paralleled that on across-hemisphere trials. Specifically, the increase in RT going from the less complex partially overlapping condition to the more complex simultaneous presentation condition did not significantly differ for divided and across-hemisphere trials and was significantly smaller for both of these trial types than for within-hemisphere trials. The similar patterns on divided and across-hemisphere trials are consistent with our hypothesis because across-hemisphere processing was generally more advantageous to performance than within-hemisphere processing in Experiment 3. Therefore, data from two distinct paradigms support our hypothesis that when within- and across-hemisphere processing are equally possible, the most efficient mode tends to underlie performance.

Our finding that the most efficient processing mode underlies performance raises the issue of how one processing mode is selected over its alternative. One possibility is that both within- and across-hemisphere processing occur simultaneously in the midline and divided conditions and that performance is determined by whichever of the two processes finishes first. However, such a horse-race model predicts that performance in the midline condition should be faster than performance in the within- and across-hemisphere conditions, which we did not observe (see Miller, 1981, for a discussion of horse-race models).

Because the levels of task complexity were blocked in all three experiments, a second possibility is that a top-down process biases midline and divided performance toward across-hemisphere processing for the more complex task situations (e.g., the NI task and the simultaneous presentation condition) but toward within-hemisphere processing for the less complex task situations (e.g., the PI task). Prior studies have demonstrated that expectancies about an upcoming task influence which single hemisphere underlies performance in split-brain patients (e.g., Levy & Trevarthen, 1976). In the intact brain, top-down processes sensitive to task complexity might bias the brain toward across-hemisphere processing for complex tasks but toward within-hemisphere processing for simpler tasks. The function of these top-down processes would be to maximize performance by selecting the most efficient processing mode for an upcoming task. It is difficult to evaluate this possibility in the present experiments because we did not vary computational complexity (e.g., PI task vs. NI task) independently of participants' expectancies regarding the complexity of the task that was to be performed (e.g., expecting PI task vs. expecting NI task). However, one way to evaluate this model in future studies would be to present the PI and NI tasks within the same trial blocks and cue participants as to which task is likely to be presented on each trial. The top-down model would be supported if the degree to which performance is subserved by within- or across-hemisphere processing on midline trials is affected by which task is cued, whether or not the cued task is the one that is actually performed.

A third possibility is that processing is automatically divided across the hemispheres whenever the processing capacity of a single hemisphere becomes taxed (Banich & Passarotti, 1999; Belger & Banich, 1998). This model posits the existence of a mechanism within each hemisphere that is sensitive to whether the hemisphere's processing capacity is being taxed during the performance of a particular task. When processing capacity becomes depleted, this mechanism might initiate a process whereby processing would be divided across both hemispheres of the brain. In contrast to the top-down model proposed above, this relatively automatic model would predict that participants' expectations about an upcoming task should not influence the degree to which within- and across-hemisphere processing underlie performance when both are possible.

More generally, our results also complement prior studies of metacontrol (e.g., Hellige et al., 1989). In particular, our studies indicate that processing may be distributed dynamically across both hemispheres for complex tasks, even when stimulus information is presented such that a single hemisphere can underlie performance. We term this task-dependent coupling of the hemispheres *coordinated control* to emphasize that although there are times when a single hemisphere dominates performance (e.g., metacontrol), there are also situations in which processing is coordinated between and ultimately controlled by both hemispheres.

Our results also have implications for the interpretation of data from functional neuroimaging studies. In some studies, there is robust bilateral activity for computationally complex tasks but mainly unilateral activity for simpler tasks (e.g., Klingberg et al., 1997). Because their paradigms made use of central presentation of stimuli, it is difficult to determine whether the observed bilateral activity reflects interhemispheric cooperation. Nevertheless, our present data suggest that the greater amounts of bilateral activity associated with increased computational demands in these studies may very well reflect an interhemispheric division of labor. Future imaging studies that use within- and across-field presentation would be helpful for resolving this issue.

Finally, our results have implications for our understanding of processing deficits observed in patient populations who have undergone commisurotomy or suffer from callosal degeneration. In particular, our data strongly suggest that at least some of the performance decrements observed at high levels of task complexity in syndromes such as multiple sclerosis, closed-head injury, and commisurotomy arise from an inability to distribute processing across both hemispheres (e.g., Banich, 1998).

In summary, our present findings provide a unifying perspective from which to view results from divided visual field studies, data from neuroimaging, and findings from syndromes associated with damage to the corpus callosum. The view supported by our data is that the degree to which interhemispheric cooperation underlies performance when within- and across-hemisphere processing are equally possible varies dynamically with task complexity. Processing is likely to be divided across both hemispheres for complex tasks but more likely to be driven by a single hemisphere for relatively simple tasks. This result extends to more naturalistic situations prior findings that an experimenter-imposed division of processing across the hemispheres facilitates the performance of complex tasks more than it aids the performance of simpler tasks (e.g., Banich & Belger, 1990). It also indicates that interactions between brain regions vary dynamically in ways that maximize the brain's limited processing capacity.

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