

## The Missing Link: The Role of Interhemispheric Interaction in Attentional Processing

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Although interhemispheric interaction via the callosum is most often conceived as a mechanism for transferring sensory information and coordinating processing between the hemispheres, it will be argued here that the callosum also plays an important role in attentional processing. Experiments will be presented that support this viewpoint, both when attention is conceptualized as a resource and when it is conceptualized as a selective mechanism for gating sensory information. Interhemispheric interaction is posited to aid attentional processing because it allows for a division of labor across the hemispheres, and allows for parallel processing so that operations performed in one hemisphere can be insulated from those executed in the other. Given this additional role for interhemispheric processing, it is suggested that the corpus callosum should be considered a component in the network of neural structures that underlie attentional control. © 1998 Academic Press

The traditional approach of researchers examining the neural bases of attention is to determine how specific brain regions contribute to the performance of specific attentional functions. For example, the thalamus has been proposed to act as a filter of incoming sensory information (e.g., LaBerge & Buchsbaum, 1990), posterior parietal regions have been implicated in disengaging attention from a particular point in visual space (Posner, Inhoff, Friedrich, & Cohen, 1987), frontal regions of the brain have been suggested to process novel stimuli (e.g., Knight, Hillyard, Woods, & Neville, 1980), and the anterior cingulate cortex appears to participate in response selection (e.g., Pardo, Pardo, Janer, & Raichle, 1990). Each of the cerebral hemispheres is also thought to play a distinct role in attentional functions. For example, it has been proposed that the right hemisphere is more involved in paying attention to global aspects of visual form whereas the left hemisphere is better able to attend to local aspects (e.g., Robertson, Lamb, & Knight, 1988; Robertson, & Lamb, 1991; VanKleeck, 1989).

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Even though most researchers conceive the neural control of attention to occur via a network of structures working in concert (e.g., Mesulam, 1981; Corbetta et al., 1981), the manner in which the interplay of these various brain structures modulates performance remains unspecified. In this paper, I will argue that the *interaction* between the cerebral hemispheres, rather than the specific processes performed by each, can influence certain aspects of attentional functioning because these *dynamic interactions modulate the processing capacity of the brain*. In this paper, I will argue that dividing processing across the hemispheres is useful when processing load is high because it allows information to be dispersed across a larger expanse of neural space. Although such a dispersal ultimately requires that information eventually be recombined and/or that processing be coordinated, I posit that under high load conditions these costs are minimal compared to the gain afforded by a division of labor. In contrast, when the computational load is light or information does not engender conflict, a single hemisphere can adequately handle the processing requirements. In this case, the dispersal of information does not add much computational power and the costs of coordination are relatively more substantial. I also posit that a dispersal of processing across the hemispheres may be useful when it allows competing processes to be insulated from one another (see Liederman, 1986 for a similar point). These dynamic interactions between the hemispheres that affect attentional processing are proposed to occur via the corpus callosum.

Sperry, in his classic work, demonstrated that the corpus callosum is the brain structure critical for allowing processing occurring in one cerebral hemisphere to be transmitted to and integrated with processing occurring in the other. In the years since his ground-breaking studies, students of brain anatomy and function have traditionally conceptualized the callosum's role as being a conduit which allows for information exchange between the cerebral hemispheres. In this paper, however, I will argue that dynamic interactions between the hemispheres via the callosum not only allow for coordination of processing between the hemispheres, but also have profound effects on attentional functioning. From this perspective, I conceptualize interhemispheric interaction as a missing link because it is "missing" from most discussions of the neural substrates of attention, and it is the "link" that allows the interplay of the hemispheres to have an effect on attentional processing.

To make this point, the present paper is organized in the following manner. First, I review a body of experimental evidence from our laboratory indicating that interaction between the cerebral hemispheres aids performance under attentionally demanding conditions. This role for interhemispheric interaction will be shown to hold regardless of whether one conceptualizes attention from a resource perspective or from the perspective of a selective mechanism that acts on sensory material or internal representations. After this discussion, I briefly review evidence from other sources suggesting that interaction between the cerebral hemispheres has attentional consequences. Finally, the

paper concludes with a discussion of possible mechanisms whereby interhemispheric interaction might modulate attentional processes.

## I. A ROLE FOR INTERHEMISPHERIC INTERACTION IN ATTENTIONAL FUNCTIONING: EVIDENCE FROM NEUROLOGICALLY INTACT INDIVIDUALS

Before we examine how interhemispheric interaction is linked to attentional processing, we need to address the issue of how we will conceptualize or define attention. There are a variety of models of attention (see for example, LaBerge, 1990), but central to most all of them is the idea that attention is the cognitive mechanism that allows us to select information in some manner—ranging from selecting particular information from the vast stream of incoming sensory information to selection of a response from among a wide variety of output options. In this paper, we will focus on two prominent conceptualizations of attention—resource models of attention and models of visual selective attention.

### *A. Interhemispheric Interaction and Attention from a Resource Perspective*

Limited resource theory (e.g., Kahnemann, 1973) assumes that the brain has a limited processing capacity and that resources must be allocated to tasks so that they can be performed. As originally conceptualized, these resources were undifferentiated and just allocated to tasks as need be, until they were depleted. Later versions of resource theories postulated multiple pools of resources (e.g., Wickens & Liu, 1988) that were allocated independently (e.g., spatial vs. verbal resources, resources for early selection vs. those used for late selection, and auditory vs. visual resources). In fact, it has been proposed that each cerebral hemisphere has a functionally distinct set of resources (e.g., Herdman & Friedman, 1985; Kinsbourne & Hicks, 1978) based on experimental studies in which greater interference is observed for two concurrently performed tasks when they both rely on the same hemisphere (e.g., two verbal tasks) than when each relies primarily on different hemispheres (e.g., one verbal and one spatial task) (e.g., Hellige & Cox, 1976).

In the subsequent discussion, I will argue that there exists a multiplicity of ways in which the component processes required to perform a complex task can be divided between the hemispheres because most all tasks (with the exception of speech output and phonetic processing) can be performed by either hemisphere (albeit in different ways and to differing degrees of competence). I will argue that interhemispheric interaction, therefore, can act as a way to dynamically allocate different computations involved in a complex task to each hemisphere, much the way parallel computers dynami-

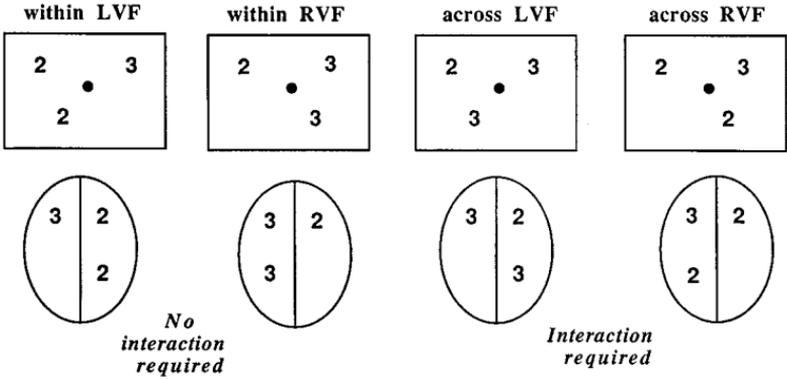
cally distribute computations across processors (e.g., see Nelson & Bower, 1990, for a discussion of parallel processing and the brain).

In this paper, I assume that the need for attentional resources will increase as the processing demands on a system increase. Here I attempt to provide some index of processing demands by examining the computational complexity of tasks. I define computational complexity as dependent on the number and sorts of transformations, operations, or computations that must be performed on an input before a decision can be reached. In our research we have demonstrated, across different modalities, that the performance of more computationally complex tasks is aided by interhemispheric interaction. Here we will just give some illustrative examples of this line of research and discuss how interhemispheric interaction might lead to such a performance advantage.

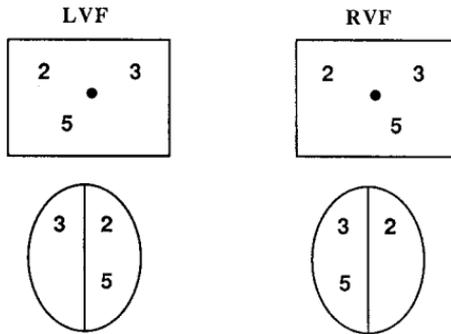
In our studies we typically compare performance under conditions in which an individual must decide if a target item matches either of two probes. To investigate the role of interhemispheric interaction we compare two types of trials: within-hemisphere trials and across-hemisphere trials (see Banich & Shenker, 1994, for the necessity of both conditions when studying interhemispheric interaction). On within-hemisphere trials, the target and matching probe are directed to the same hemisphere and hence no interhemispheric interaction is required to make a decision. In contrast, on across-hemisphere trials, the target and matching probe are positioned in different visual fields, and hence directed to different hemispheres. Thus, the hemispheres are forced to communicate if the task is to be performed correctly. Because split-brain patients, for the most part, cannot make such an identity comparison between items in each visual field (see Sergent, 1990), we assume that the comparison of items presented in opposite visual fields must rely on callosal transfer. Thus, comparison of these two types of trials allows us to determine the effect of interhemispheric interaction on performance. Our typical experiments are designed so that half the trials contain a match and half do not. For both match and mismatch trials, the bottom target item is in the left visual field (LVF) half of the time, and in the right visual field (RVF) the other half (See Fig. 1).

Performance on within- and across-hemisphere trials is compared under two conditions: a less complex condition and a more complex condition, which vary in the number of computational steps that must occur for a task to be performed correctly. Traditionally, our less complex task has involved a simple perceptual matching task in which the participant must decide if two items are identical (e.g., A A). In our studies we have used a variety of stimuli including digits (Banich & Belger, 1990, Exps. 2 & 3), letters (Banich & Belger, 1990, Exp. 1; Belger & Banich, 1992), and geometric shapes (Banich, Passarotti, & Chambers, 1994; Banich & Passarotti, in preparation, a). The more complex condition always requires at least one extra computational step above and beyond simple perceptual analysis. We have used a

**Match Trials**



**Mismatch Trials**



**FIG. 1.** Examples of the trial types used to examine the effects of interhemispheric interaction on performance. On match trials, the bottom target item matches one of the top two probes, whereas on mismatch trials there is no such match. There are two classes of match trials. In one (within RVF and within LVF trials), the two matching items are presented in the same visual field, and hence interhemispheric interaction is not required to reach a decision. In the other (across RVF and across LVF trials), the matching items are directed to different visual fields, and interhemispheric interaction must occur for the correct decision to be reached.

variety of tasks including a name-matching task (e.g., A a) (e.g., Banich & Belger, 1990; Exp. 1) which not only requires perceptual analysis but also the extraction of a name- or case-specific letter code, a summation task that requires two numbers to be added (Banich & Belger, 1990; Exp. 3), a ordinal task that requires the value of two numbers to be compared (Banich & Belger, 1990; Exp. 3), a spelling task that requires a comparison between a target word and two letters (Banich, Goering, Stolar, & Belger, 1990), and a form categorization task that requires the determination of whether two perceptually distinct forms (e.g., an isosceles triangle and equilateral triangle) belong to the same category (i.e., triangle) (Banich, Passarotti, & Cham-

bers, 1994; Banich & Passarotti, in preparation, a). Invariably, we obtain a significant interaction between trial type (within-hemisphere, across-hemisphere) and condition (less complex, more complex). Typically, our results yield superior performance on across-hemisphere trials as compared to within-hemisphere trials for the more computationally complex, and hence more attentionally demanding task, a pattern that is not observed for the less demanding task. Thus, we believe that interhemispheric interaction is a means for modulating the attentional capacity of the brain.

In our laboratory, we have demonstrated, in two different manners, that this role for interhemispheric interaction is a general phenomenon: first, we have shown it to hold across different modalities, and second, we have found it to hold over different manipulations of attentional and computational complexity. I will now discuss each set of findings in turn.

All the studies discussed above were performed in the visual modality. Hence, one might wonder whether the effect we observe is really specific to interhemispheric interaction in general, or whether it only holds for interaction involving visual information. To investigate this issue, we conducted studies (Banich & Passarotti, 1995; Passarotti & Banich, in preparation) meant to be an auditory analogy of one of our prior visual studies: one in which a less computationally complex physical-identity task with digits was compared to a more complicated ordinal task (Banich & Belger, 1990; Exp. 3). In our auditory task, an individual heard two pairs of dichotically presented items presented in succession with an ISI in between (which was set at 100 msec in one study and 250 msec in another). In the first pair, one item was the target digit and the other item was the name of a common animal (e.g., dog).<sup>1</sup> The second pair consisted of two digits. Participants decided whether either of the two probe digits in this second pair matched the previously presented target. In the physical-identity task, participants decided if the target and one of the probes was identical while in the ordinal task they decided if one of the targets was smaller in value than the probe. Our results for the physical-identity task indicated that when the matching digits were presented to the same ear (and hence the same hemisphere), performance was superior than when digits were presented to opposite ears. However, this effect was significantly reduced for the ordinal decision task. Thus, as observed in the visual modality, there was an interaction such that the utility of interhemispheric interaction is greater for the more complex and attentionally demanding task than for the less complex one.

We have also obtained a similar interaction with a somatosensory equiva-

<sup>1</sup> The initial pair was constructed in this manner so that each ear was receiving an item, creating dichotic conditions under which the hemisphere contralateral to the ear receiving an item will be more involved in processing it (i.e., the left hemisphere will be more involved in processing information from the right ear and the right hemisphere will be more involved in processing information from the left ear).

lent of our visual shape tasks (e.g., Are these both forms perceptually identical? Are both these forms triangles?). In our somatosensory task, a tactual array consisting of three shapes each constructed out of sandpaper is hidden behind a screen (to preclude the receipt of visual information). Each of the three shapes is felt individually for 5 seconds. First, an index finger of one hand feels the target shape. Then the fifth finger (pinkie) of a hand feels the first probe and afterwards the fifth finger of the second hand feels another probe (Which index finger is used to feel the target is counterbalanced across trials as is the order of which fifth finger feels a probe first). In half of the matching trials, the two matching shapes are felt by the same hand (within-hemisphere trials) and in the other half, the target felt by the index finger of one hand matches with the probe presented to the fifth finger of the other hand (across-hemisphere trials).

A number of characteristics of this task make the relationship between the category task and the physical-identity task different in the somatosensory modality than in the visual one. The size of these sandpaper shapes precludes them from being felt all at once, and hence their sides must be felt one at a time in a serial manner.<sup>2</sup> Because of this constraint, the shapes are not perceived holistically as is the case in the visual modality. Thus, in the somatosensory modality the category task is less computationally complex, since the person only need detect whether both items have the same number of sides. In contrast, in the physical-identity task, participants must not only determine whether both items have the same number of sides, but whether each side is the same length as well. For the less demanding category condition we found that performance on within-hemisphere trials was significantly more accurate than on across-hemisphere trials, a difference that was not observed on the physical-identity task (Passarotti & Banich, in preparation).

Thus, interhemispheric interaction aids performance under attentionally-demanding conditions across all three modalities: visual, auditory and tactile. Because information in each of these sensory modalities is likely to be transferred by different segments of the callosum (visual information via the splenium, auditory information via the anterior splenial region and tactile information via the posterior section of the body of the callosum; e.g., DeLacoste, Kirkpatrick, & Ross, 1985; Rugg, Milner, & Lines, 1984), this convergence across modalities makes it more likely that we are observing a general overall function of the callosum, rather than the functioning of a particular callosal region.

Another issue to consider regarding the generality of our findings is that in all the tasks discussed so far, task complexity (and hence attentional demands) were manipulated by varying the complexity of the decision process (i.e., by adding additional computational steps above and beyond perceptual

<sup>2</sup> In pilot work, we found that participants found it too hard to distinguish between smaller shapes that could be felt in a single pass.

analysis). Hence, we wished to determine whether a similar pattern would be observed when complexity was manipulated in a different manner. To address this issue, we conducted studies in which we compared the relative advantage of across- as compared to within-hemisphere processing on three tasks: in the first, a physical-identity decision had to be made by comparing a target item to two probe items (i.e., 3-item physical-identity condition). In the second, a physical-identity decision had to be made by comparing a target item to four probe items (i.e., 5-item physical-identity condition). This second condition is more computationally demanding than the first because it requires the perceptual processing of two additional items and because, probabilistically, it requires additional comparisons with the target before a decision can be reached. This 5-item physical-identity condition was also compared to a third condition, a 5-item name-identity condition in which participants decided if a target matched any of 4 probes with regard to their names (e.g., A a). This condition is more complex than the 5-item physical-identity condition with regards to decision processes because the items not only need to be perceptually processed but also a name or case-specific code must be extracted from them (Belger & Banich, 1992; Belger & Banich, in press). We found that across-hemisphere processing was more beneficial on the 5-item physical-identity condition than the 3-item physical-identity condition. This result indicates that an increase in attentional demands due to increased perceptual processing and/or comparison processes has the same effect as we had observed previously when the complexity of decision processes were increased. We also replicated our prior findings with regards to decision complexity because we found that across-hemisphere processing was even more beneficial to performance relative to within-hemisphere processing for the 5-item name-identity condition than the 5-item physical-identity condition. Thus, our results demonstrated that interhemispheric interaction aids performance regardless of whether attentional demands are increased by the nature of the decision process or by the perceptual demands and/or comparison processes required by the task.

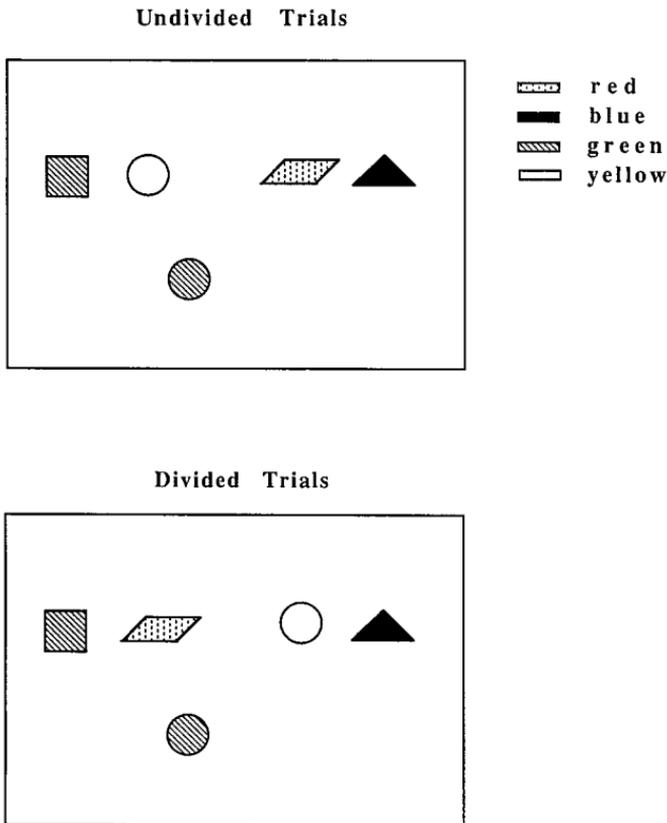
One way of understanding our findings is to conceive of across-hemisphere trials as allowing for a division of processing that cannot occur as readily or as efficiently on within-hemisphere trials. We have argued that whether interhemispheric processing aids task performance depends on two competing factors. One factor is a division of processing that occurs on across-hemisphere trials which facilitates the directing of critical information to different resource pools. The other factor is the coordination of processing that must occur by necessity on across-hemisphere trials if a correct response is to be emitted. Whether or not interhemispheric interaction aids task performance depends on the relative balance between these two factors. When a task is simple, we conceptualize that the computational demands on a single hemisphere are not so great, so that dividing processing across the hemispheres provides little or no advantage in computational power. Furthermore,

because of the cost associated with coordinating processing across the hemispheres, interhemispheric interaction may actually be deleterious to task performance. In contrast when a task is difficult, an advantage is accrued by dividing processing across the hemispheres because the subcomponents of a task can be divided between the hemispheres. Not only can these subcomponents be processed by different resource pools,<sup>3</sup> but in addition they can be processed in parallel. In a moment we will describe an experiment that supports such a contention. Although the cost of coordination remains, we posit that the advantages of parallel processing more than outweigh such coordination costs. As an analogy, consider that when you are given a simple task, it is often easier to perform it yourself, rather than trying to coordinate your work with that of a colleague. However, as the task gets harder, the time spent in meetings coordinating work with a colleague is worthwhile because the work that each of you can accomplish independently increases the overall amount of work that can be performed.

Other experiments we have conducted support the contention that it is indeed a division of labor and the ability to process information in parallel across the hemispheres under attentionally demanding conditions that leads to the across-hemisphere advantage. In one experiment, we have obtained direct evidence that the across-hemisphere advantage is most evident under conditions in which parallel processes must occur (Banich & Passarotti, in preparation b). In another, we have shown that when the requirements of an attentionally-demanding task constrain processing to one hemisphere, the across-hemisphere advantage disappears (Belger, 1993; Belger & Banich, in press). We will discuss each of these experiments in turn.

To examine whether the benefit afforded by parallel processing under attentionally-demanding conditions leads to the across-hemisphere advantage, we devised an experiment in which two conditions were compared, one of which would be aided by the opportunity for parallel processing and one of which would not. In this study (Banich & Passarotti, in preparation, b), participants saw a 5-item display with a target item in one visual field and four probe items, two presented in each visual field (see Fig. 2). All items were colored geometric shapes (e.g., a blue triangle). In one condition, the OR condition, the participants decided if the target item matched any of the probe items either with regard to color or with regard to shape. Thus, only one match need be detected, and hence only one type of operation (e.g., shape matching) need occur for a match decision to be reached. In the other condition, the AND condition, the participants were instructed to make a match decision only if the target matched one probe with regard to color

<sup>3</sup> We do not necessarily assume here that resources are undifferentiated within a hemisphere, but rather that resources in different hemispheres are more distinct than those within a hemisphere.



**FIG. 2.** Displays used to examine parallel processing between the hemispheres. For all match trials in both the OR and the AND conditions, one probe matched the target with regards to color and another matched with regards to shape. In the undivided trials, the two matching shapes were presented to the same hemisphere whereas in the divided trials, each hemisphere received a matching item. In the OR condition, only a single match need be detected (either on the basis of color or shape) for a match response to be emitted. In contrast, in the AND condition, a match both with regards to color and another with regards to form had to be detected for a match response to be emitted. The same match displays were used for both the OR and AND conditions.

and another with regard to shape. Thus, in this condition, two distinct operations, color-matching and shape-matching, needed to be performed for a correct response to be emitted.

The critical contrast in this experiment was between those match trials in the AND condition in which the probe item matching in color was directed to one hemisphere and the probe item matching in shape was presented to the other (divided trials) and those trials in the AND condition when both the probe item matching in shape and the probe item matching in color were

presented to the same hemisphere (undivided trials). Since two operations had to be performed, we predicted that performance would be better on divided trials, since such an arrangement provided the possibility for one hemisphere to perform one type of operation (e.g., a match based on color) while the other hemisphere could perform another type of operation (e.g., a match based on shape). In contrast, on undivided trials, analysis of both form and color would have to be performed by the same hemisphere, not allowing for a division of labor.

Furthermore, we predicted that any advantage for divided trials should be greater for the AND condition than the OR condition. Although the match stimuli in the OR condition were identical to those in the AND condition, in that on each trial a match existed both on the basis of color and on the basis of form, only one match need be detected (and only one operation need be performed) in the OR condition. Hence, we predicted that for the OR condition, divided trials should not produce a performance advantage. As expected, we observed a significant interaction, such that divided trials led to an advantage in the AND condition but not in the OR condition. These findings provide evidence that the ability to perform operations in parallel across the hemispheres does indeed lead to a performance advantage. Hence, we have garnered support for our supposition that it is the division of processing that leads to the across-hemisphere advantage we have observed in our other studies.

The results of this experiment build upon some of those obtained by Liederman and colleagues who have discussed the possibility that parallel processing in the hemispheres could aid performance. In some of their studies, they demonstrated that more letters could be identified when one hemisphere received two inverted letters and the other two upright ones (separated condition), as compared to a condition in which each hemisphere received one upright and one inverted letter (unseparated condition) or a condition in which one hemisphere received all four letters (Merola & Liederman, 1990; Liederman, Merola, & Hoffman, 1986; Merola & Liederman, 1985). Liederman interpreted these findings as providing evidence that a division of inputs to the hemispheres leads to a performance advantage when competing processes were separated, so that each process is performed by a separate hemisphere.

Her results, however, do not demonstrate that it is parallel processing *per se* that leads to the performance advantage. In her paradigm, participants had to report items and on average reported two of the four items. Thus, in the separated condition, it is possible that participants just reported items from one hemisphere and not the other, which would not qualify as parallel processing. However, the data are not presented in their paper in a way that would allow one to determine if such a strategy was indeed employed by participants. In contrast, in our study, the paradigm was constructed so that both matches *had to be detected* in the AND condition before a decision

could be reached. Hence, both processes had to be performed before a decision could be reached. The faster reaction time and higher accuracy in the divided trials than the undivided trials of the AND condition suggests that these processes could occur in parallel on the divided trials in a way that was not possible on the undivided trials.

Other work of Liederman's pointing to the possibility that parallel processing leads to a performance advantage comes from another study in which individuals had to add one digit to a centrally-presented number and subtract another digit from this same centrally presented number (Liederman, 1986). In this case, performance was superior when each digit was presented to a different hemisphere than when both digits were presented to the same hemisphere, which Liederman interpreted as occurring because each hemisphere was involved in a distinct operation.

However, in this study the advantage observed on those trials in which information is directed to different hemispheres may have occurred either because of a division of processes or because of a division of inputs. Performance is better on bilateral trials, in which each hemisphere receives half the number of inputs than that provided to a hemisphere on unilateral trials. Hence, it may be the division of inputs, rather than a division of processes, that leads to the performance advantage. In our studies, the number of perceptual inputs is identical on both divided and undivided trials (i.e., 3 items to one hemisphere and 2 to the other), precluding the possibility that our results emanate from the number of perceptual inputs per hemisphere. Rather, our method allows us to be sure that it is the division of processing, rather than a division of inputs, that leads to the performance advantage. Furthermore, although Liederman's 1986 study provides tentative evidence that a division of inputs is useful when two operations must be performed, it does not provide evidence that such an advantage would not occur if only one operation is performed. In contrast, our study demonstrates that the advantage of parallel processing is unique to concurrent performance of two operations, as we only find the divided advantage for the AND condition, but not the OR condition.

The other piece of evidence suggesting that a division of processing is critical to producing the across-field advantage comes from a study in which we chose a demanding task whose major component can only be performed by one hemisphere and hence could not be divided across the hemispheres (Belger, 1993; Belger & Banich, in press). We predicted that even though this task was similar in complexity to those we had used in other studies, no across-hemisphere advantage would be observed. To investigate this hypothesis we used a rhyme task in which the bottom target item was a three-letter target word (e.g., SEA). Participants decided if this word rhymed with either of two letters (e.g., B and F), one of which was presented in each visual field. This task is similar in perceptual complexity to the 5-item physical- and name-identity tasks discussed earlier, and similar in decision complexity to

that of the name-identity task. Thus, on the basis of an analysis of resource demands, the rhyme task is as demanding as the other tasks on which we have obtained an across-hemisphere advantage.<sup>4</sup>

However, the rhyme task is unique in that the grapheme-to-phoneme conversion required to make the rhyme decision is one that relies critically and solely on the left hemisphere (e.g., Rayman & Zaidel, 1991). Hence, unlike our other complex tasks, a substantial portion of this task cannot be subdivided. Even though earlier stages of perceptual processing can be divided across the hemispheres, the final stage that is critical for reaching a correct decision (i.e., a determination of phonology) cannot be divided across the hemispheres.

In fact, on this task, we observed neither a significant within- nor a significant across-hemisphere advantage, supporting our contention that it is the ability to divide processing across the hemispheres that leads to a performance advantage on across-hemisphere trials. Although it might seem odd that we did not obtain a within-hemisphere advantage on this task, one must consider that other subcomponents of the task, such as perceptual processing and identification of items could be performed by either hemisphere, which may account for the lack of a within-hemisphere advantage. Thus, when the characteristics of a complex task are such as to preclude a division of processing across the hemispheres, the across-hemisphere advantage disappears.

The evidence reviewed above illustrates that across-hemisphere processing leads to a performance advantage under attentionally demanding conditions, and that such effects generalize across modalities and across various manipulations of demands. Furthermore, our results indicate that the advantage on across-hemisphere trials is likely to result because across-hemisphere trials allow each hemisphere to process information in parallel. Because the resource pools in each hemisphere appear to be somewhat distinct, a separation of processing leads to a performance advantage as compared to when processing must be performed by a single hemisphere.

### *B. Interhemispheric Interaction and Attention from a Visual Selective Perspective*

Other models of attention assume that it is a mechanism which acts to gate or select specific portions of the incoming sensory stream. Although there are a variety of models of selective attention (e.g., Treisman & Gelade, 1980; or see Kramer, Coles, & Logan, 1996, for a number of different models), they generally all assume that attention allows certain information to be selected for additional processing while other information is not processed as fully, is ignored, or is suppressed.

<sup>4</sup> In fact, the RT on the rhyme task was as long or longer as the other computationally demanding tasks, and had a similar error rate.

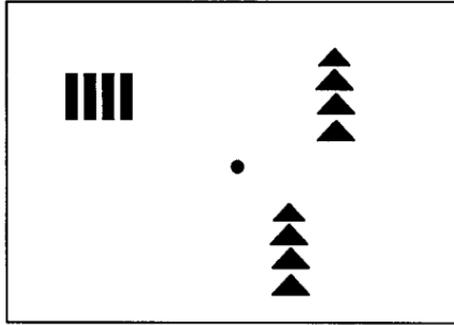
We will argue that interhemispheric interaction might influence such selective processes in two ways. First, one can consider that the need to select material will increase the computational requirements of a task as compared to when no such selection is needed. Thus, as has just been argued, interhemispheric interaction may aid processing under such demanding conditions because it allows for a dynamic reallocation of resources across the hemispheres. Another possibility is that a division of processing across the hemispheres may allow interfering processes to be insulated from each other (e.g., Merola & Liederman, 1985), even if the outputs of the processing performed by each hemisphere must be integrated later on. We have examined these issues by using two different selective attention paradigms. In the first paradigm, attention is directed to an item's global form in one condition and to its local elements in another. In the second paradigm, attention must be directed to one attribute of a stimulus (e.g., form) while another is ignored (e.g., color).

In the global-local paradigm as initially popularized by Navon (1977), an individual sees a hierarchical figure, which is a large global figure made up of local elements (e.g., a large S composed of little Ss). In one condition, the individual is instructed to attend to the global shape and base a decision on an item's characteristics at that level. In another condition, the individual is instructed to attend to the local elements and base a decision on an item's characteristics at that level. Generally, there are two types of trials, those in which the overall shape and the component parts are identical (e.g., a large S composed of small Ss), which are referred to as consistent trials, and those in which the overall shape and the component parts lead to different decisions (e.g., a large S composed of small Hs), which are referred to as inconsistent trials. Usually, responses to inconsistent trials take longer than to consistent trials because information at the irrelevant level on inconsistent trials must be ignored to avoid an incorrect response.<sup>5</sup>

If, as we have posited, interhemispheric interaction plays a role in attentional processing, then we should observe that it moderates performance under conditions of selective attention. To test this hypothesis we used a version of our standard three-item display (refer back to Figure 1) in which subjects decided if hierarchical figures matched at the prespecified level to which they were told to attend (e.g., global level). In some cases, the matching items were identical at both the global and local level (consistent trials) and sometimes they matched at the attended level but not at the unattended level (inconsistent trials) (see Fig. 3). As predicted, we found that the interference on inconsistent trials relative to consistent trials was significantly reduced when matching items were presented to different hemispheres (across-hemi-

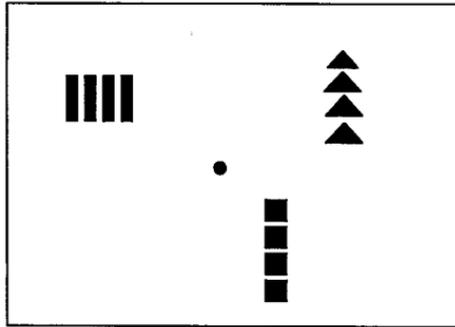
<sup>5</sup> This inconsistent effect is usually more evident when individuals must attend to information at the local level and ignore the global rather than when they must attend to information at the global level and ignore the local.

### Consistent Trials



Global: Match; Local: Match

### Inconsistent Trials



Global: Match; Local: Mismatch

**FIG. 3.** Stimuli used to investigate the effect of interhemispheric interaction on selective attention in a global-local paradigm. The participant must base the decision on the characteristics at a prespecified level (e.g., global). Shown here are within-hemisphere match trials when attention is directed to the global level. Notice that in the consistent trial, the information at the unattended level (i.e., local) also matches but that on inconsistent trials it does not.

sphere trials) than when presented to the same hemisphere (Weissman & Banich, submitted).<sup>6</sup>

<sup>6</sup> It should be noted that this result stands in stark contrast to the proposal by Robertson, Lamb and Zaidel (1993) that interhemispheric interaction is actually the locus of global/local interference. We believe that this discrepancy may arise for two reasons (see Weissman & Banich, submitted for a further discussion of this issue). First, Robertson and colleagues make their inference based on null results obtained with split-brain patients. These null results may occur for other reasons (e.g., variability in data coupled with a lack of statistical power). Second, the studies they cite to bolster their claim typically infer interhemispheric interaction as the source of the interference effect but do not have the appropriate contrast to show that the effect is indeed specific to interhemispheric interaction (see Banich & Shenker, 1994 for a discussion of the required contrast). Finally, it should be noted that Weekes, Carusi, and

These findings can be conceptualized within either of two frameworks for understanding attentional effects that we have discussed; one with regard to resources and the other with regard to insulation of processing. With regards to attention as a resource, we can consider that on both the consistent and inconsistent trials, information must be selected at the relevant level, but on inconsistent trials, information from the irrelevant level must be filtered out in order to reach a correct decision in a way that needn't occur on consistent trials. Hence from a computational perspective, there are more processing demands involved in the inconsistent than consistent condition. Supporting such a supposition are the results of an additional manipulation included in this experiment which we have not yet discussed. On some trials, we had hierarchical stimuli that were composed of few local elements (as shown in Figure 3) and on other trials, the stimuli were composed of many local elements. Researchers examining the perceptual processing of global and local aspects of form have suggested that the two levels of hierarchical figures (i.e., the global and the local) are less separable when composed of few local elements as compared to many local elements (e.g., Kimchi & Palmer, 1985). They posit that in the few element arrays, information at both the local and global levels contributes to the perception of overall form, so that changing the local elements influences the perception of the overall form. In contrast, in the many element displays, the local elements act more as texture, so that changing them does little to the overall perception of the form, suggesting that in these displays, the global and local level are more separable. The result is that directing attention to the prespecified level in the few element displays is more attentionally demanding because it requires additional computational steps compared to the many element displays. In the few element displays, decomposition of the overall visual pattern must occur if attention is to be directed to the prespecified level. This process is not as necessary when attending to only one level of the many element displays. Consistent with the idea that interhemispheric interaction is more helpful under attentionally demanding tasks, we found that interhemispheric interaction aided performance to a greater degree for the few element displays than for the many element displays.

Another way to conceptualize our results is to consider the possibility that the reduction in interference between the two levels might occur because inconsistent material is less effective at creating interference when directed to the opposite hemisphere. For example, if the individual is told to attend to the global level, it is possible that global information is given priority in interhemispheric transfer and information from the local information is suppressed. In contrast, when the inconsistent information is presented to the same hemisphere, such a suppression of local information may be less

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Zaidel (1997) have suggested that global/local interference may be mediated intrahemispherically in split-brain patients.

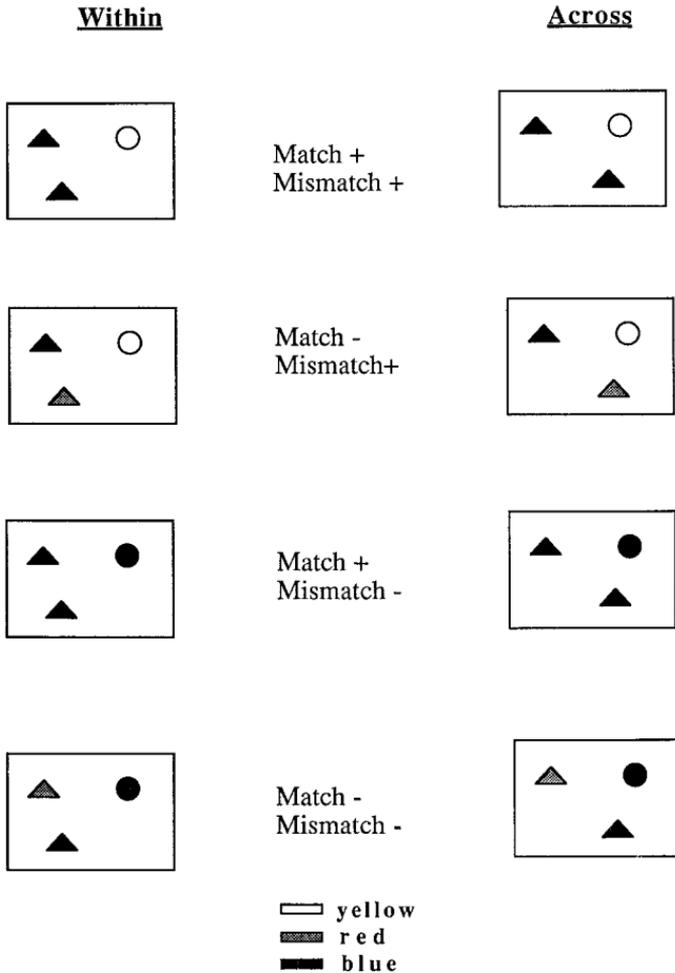
possible. In this case, there would be a gating of information in interhemispheric transfer that would serve to reduce interference.

We have also observed interhemispheric interaction to aid in another condition under which selective attention must be utilized, that is when attention has to be directed to one attribute of an item (i.e., its form) while another has to be ignored (i.e., its color). In this study, participants made decisions about colored geometric shapes (Banich & Passarotti, in preparation, a). The relationship between the shape of the items and their color varied across trials. In some trials, the color provided information that was redundant with the decision reached by attending to form (i.e., both the target and matching probe were the same color and the non-matching probe was a different color). In other cases, color provided ambiguous information—being consonant with the shape decision for one probe but conflicting for the other (i.e., the matching probe was the same color as the target (consonant), but so was the non-matching probe (conflicting); the matching probe was a different color than the target (conflicting), but so was the non-matching item (consonant)). In still other cases, color provided directly conflicting information (e.g., the matching probe was a different color than the target, but the mismatching probe was the same color as the target) (see Fig. 4).

One can conceptualize these trials as varying in the degree of selective of attention required. In the first condition, the color of the items needn't be filtered to as large a degree in order to reach a correct decision because it provides a redundant cue, aiding in the identification of the matching items (which are the same color) and distinguishing the mismatching item (which is a different color). In contrast, in the last condition, the probe's color must be filtered to a much greater degree because in this condition color is completely misinformative; it obscures the relationship between the two matching items (since they are different colors) and falsely makes the mismatching item seem similar to the target (since it is the same color as the target). We found that the across-hemisphere advantage (60 msec) was significantly larger in this last condition in which color is completely misinformative and hence requires the greatest degree of filtering, as compared to the other conditions in which the average across-hemisphere advantage was only 34 msec. Thus, as with the global-local paradigm we have found that across-hemisphere processing is useful to performance when the selective attentional demands are high.

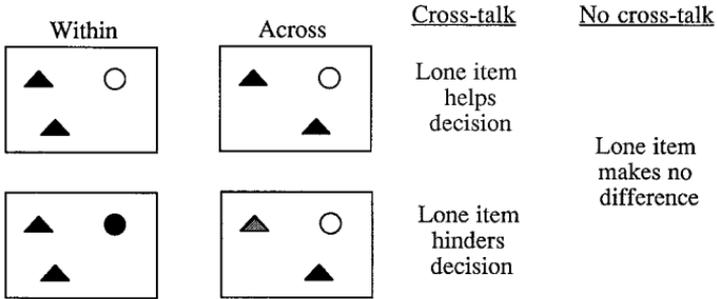
This particular experiment also provided us with some insights into the way in which processing might be insulated between the hemispheres, and the conditions under which that insulation might occur most readily. To examine the question of insulation of processing, we examined performance on specific pairs of trials (see Fig. 5).

In each pair, identical information was projected to the hemisphere that received 2 items (e.g., compare the top left and bottom left item in Fig. 5a). What differed between each pair was the nature of the single item projected

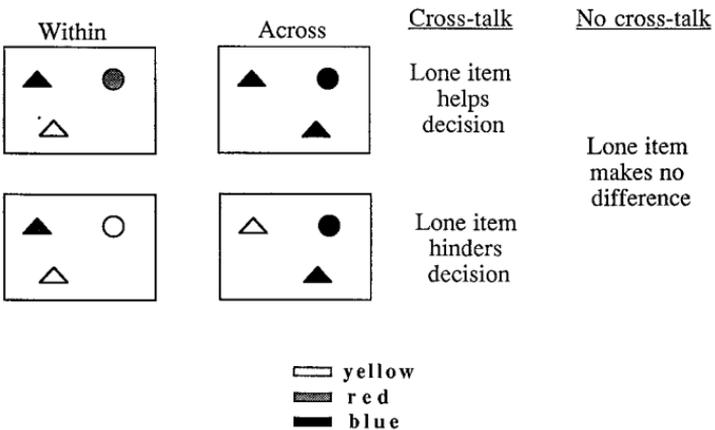


**FIG. 4.** The variety of trials in the experiment in which attention is selectively paid to form, while color is ignored. The trials varied in how much color provides distracting information and hence how much color needed to be selectively ignored, with trials on the top requiring less selection and those on the bottom requiring more. In some trials, (from the top), color aided in identifying both matching (+) and mismatch probes (+), as the matching probe was the same color as the target, while the mismatching probe was a distinct color. In other trials, color did not help to identify the matching probe (-) because its color was distinct from that of the target, but did help to distinguish the mismatching probe from the target (+) because its color was also distinct. In still other trials, color helped to identify the matching probe (+) because it was the same color as the target, but did not help to distinguish the mismatching probe (-) because it was also the same color as the target. The most selection was required on trials in which color did not help to identify the matching probe (-) because it was a different color, and also did not help to identify the mismatching probe (-) because it was the same color as the target.

## a) Color redundant within visual field



## b) Color conflicting within visual field



**FIG. 5.** The pairs of trials used to investigate the degree of insulation of processing across the hemispheres. What differs between each pair is whether the color of the lone item would aid in making the decision (top) or hinder it (bottom) if cross-talk occurs between the hemispheres. (a) In some trials, color provides a redundant cue for processing the two items directed to a single hemisphere (either the two items match in shape and are the same color, or are different shapes and different colors). (b) In other trials, color provides a conflicting cue for processing of the two items directed to a single hemisphere (either the two items match in shape and are different colors, or are different shapes but the same color).

to the opposite hemisphere. In some cases, this lone item matched the target in color whereas in other cases it did not. We reasoned that if there were cross-talk between the hemispheres about color, we would expect to see a difference in performance across the two types of trials in each pair with better performance on trials in which the lone item's color reinforces its relationship in shape to the target. In contrast, if there were little or no cross-talk about color between the hemispheres, then performance across both types of trials in each pair should be similar because the color of the single

item directed to the opposite hemisphere should have little influence on performance.

Because we were interested in the degree to which selective mechanisms would have to be at work on each pair of trials, we also examined the relationship between the two items projected to a single hemisphere (regardless of whether it was a within- or across-hemisphere trial). For some pairs of trials, color provided a redundant cue (i.e., the shapes within a visual field were identical and the same color; the shapes within a visual field were different and were different colors). In other cases, color provided a conflicting cue (i.e., the shapes within a visual field matched but were different colors; the shapes within a visual field were different, but were the same color). Hence, more filtering of color would be needed for the latter pairs than the former ones if a correct decision about the relationship between the items' forms was to be reached (refer back to Fig. 5).

We observed that the amount of cross-talk/insulation about color observed on match trials depended on the amount of selection required by the hemisphere that received two items. When color provided a redundant cue with regards to the shape of the items (i.e., both items in the same visual field were the same shape and were the same color), the color of the item in the opposite visual field had no effect on performance. This finding suggests that under such conditions information about the irrelevant attribute (i.e., color) of information presented to the opposite hemisphere can be effectively suppressed. In contrast, when color provided a conflicting cue to the hemisphere that receives two items (i.e., the items matched but were different colors, or they did not match and were the same color), the color of the item in the opposite visual field influenced performance. In this case, responses were faster when the color of the item in the opposite visual field helped to reinforce the relationship to the target (i.e., it was the same color as the target and matched in shape), than when it did not (i.e., it was the same color as the target but didn't match in shape).

Hence, it appears that the degree to which insulation occurs can vary depending on the degree of selection that must occur. When information presented to one hemisphere requires selection (e.g., color must be filtered out from shape), information presented to the other hemisphere has an influence, indicating that there is cross-talk and a lack of insulation of processing. However, when less filtering is needed because color provides a redundant cue, there appears to be little or no cross-talk, providing evidence for insulation of processing.

What conclusions can we draw from these two studies? In both, a greater across-hemisphere advantage was found when the need for selective attention was larger. In the study which required selective attention to form, we find the greatest across-hemisphere advantage when color provides conflicting information both with regard to the relationship between the target and matching probe (i.e., they are different colors) as well as to the relationship

between the target and non-matching probe (i.e., they are the same color). Likewise, we found in the global-local study that the across-hemisphere was greater when matching items were inconsistent at the unattended level than when they were consistent, and more so for the few element arrays than the many element arrays.

The study in which we examined selective attention to form also provides evidence that when a hemisphere receives conflicting information it may bias the system away from insulation of processing and toward interaction with its partner. Although on the surface this result may appear to be contradictory to our prior suggestion that across-hemisphere processing may allow for greater insulation of processing in the global/local paradigm, it is not since there are important differences between the processing demands in these two experiments. In the case of the global/local paradigm, we are specifically looking at whether the conflict arises on within-hemisphere as compared to across-hemisphere trials, and found that the conflict appears to be better managed when divided across the hemispheres. In the paradigm in which the participant pays selective attention to shape, we are examining the degree to which cross-talk occurs when there is within-hemisphere conflict as compared to when there is no within-hemisphere conflict. Thus, these two issues are orthogonal and should not be confused. In the former case we are comparing conflict on within- as compared to across-field trials; in the latter we are only examining the degree of conflict engendered by information sent to a single hemisphere.

## II. A ROLE FOR INTERHEMISPHERIC INTERACTION IN ATTENTIONAL FUNCTIONING: CONVERGING EVIDENCE

Our studies on neurologically intact individuals just reviewed provide evidence that interhemispheric interaction affects attentional abilities. However, such an assertion would be bolstered if there were converging evidence from other sources. It is such additional evidence that we will now review briefly.

Converging evidence for our hypothesis is provided by split-brain patients in whom the cortical commissures have been severed. If the corpus callosum plays a role in attentional functioning, then we would predict that there should be attentional sequelae of disconnection of the hemispheres. In fact, the attentional functioning of split-brain patients differs from that of neurologically intact individuals in a number of ways, including the ability for sustained attention, for dual-task performance, for visual search and for selective attention.

Split-brain patients have difficulty sustaining attention for long periods of time, especially on tasks requiring mental concentration and characterized by minimal external stimulation. Because this phenomenon occurs across the visual, auditory and somatosensory modalities, it is unlikely to be driven

by perceptual factors (Dimond, 1976, 1979), but rather probably represents a more central effect. Although such decrements may not be observed in active vigilance tasks, such as when the patient is involved in a continuous sorting task and can decide how quickly to sort the items and with what interval, decrements are observed when the patient has to monitor for a stimulus under experimenter control (Ellenberg & Sperry, 1979).

Dual-task performance in another arena in which the performance of split-brain patients diverges from that of neurologically intact subjects. Although there are some reports that split-brain patients are better able to perform two tasks concurrently than neurologically intact subjects (e.g., Holtzman & Gazzaniga, 1985) (presumably because interference between the processing occurring in each hemisphere is reduced), there is a larger body of evidence suggesting that split-brain patients exhibit a decrement in performance compared to neurologically intact subjects under dual-task conditions (e.g., Holtzman & Gazzaniga, 1982; Kreuter, Kinsbourne, & Trevarthen, 1972; Teng & Sperry, 1973, 1974). These decrements may occur even though split-brain patients exhibit no deficit under single-task conditions as compared to neurologically intact individuals. Hence, the dual-task decrement cannot be attributed to greater difficulty of the patients to perform each of the single tasks (as compared to neurologically intact subjects). Furthermore, in some cases (e.g., Kreuter, Kinsbourne, & Trevarthen, 1972) when two tasks rely on the same hemisphere (e.g., verbal output and right-hand tapping both of which rely on the left hemisphere) severe decrements relative to neurologically-intact controls can be seen as task complexity increases (e.g., reciting the alphabet as compared to reciting every other letter of the alphabet, A, C, E, G . . .). The much greater decrements observed in split-brain patients than neurologically intact controls under demanding dual-task conditions suggest that the callosum normally acts as a mechanism for dispersing large processing loads across the hemispheres, a mechanism that cannot be invoked in the split-brain patients because of commissurotomy.

A third arena in which split-brain patients exhibit different attentional abilities than neurologically-intact subjects is in the area of visual search. With regard to directing attention to a particular spatial location, most research suggests that split-brain patients have a unified attentional system mediated through subcortical commissures because a cue in one hemifield can cue the detection of a subsequent target in the opposite hemifield (see Gazzaniga, 1987, for a review of these findings, as well as Zaidel & Rayman, 1994). However, in the case of visual search, each hemisphere has the ability to scan space separately for a target. For example, Luck, Hillyard, Mangun and Gazzaniga (1989) compared the performance of a split-brain subject to that of neurologically-intact individuals on a conjunction search (e.g., search for a rectangle that is blue on top and red on the bottom in a field of rectangles that are red on top and blue on the bottom). The items were either restricted to one visual field (unilateral condition) or divided between them (bilateral

condition), and the number of items in a display was varied systematically. For neurologically-intact individuals, the search rate (as inferred from the slope of the line relating RT to number of items in the display) was identical on unilateral and bilateral trials. In contrast, for the split-brain patient, the search rate on bilateral trials was double that on unilateral trials, suggesting that each hemisphere was able to search its half of visual space independently of the other.

Attentional processes in split-brain patients also diverge from that of neurologically intact subjects in the arena of selective attention to a specific feature of a stimulus. One well-known attentionally based interference effect that is absent or reduced in split-brain patients is the Stroop effect. In the Stroop paradigm, individuals take longer to name the color in which a word is printed when the letters of the word spell a color that is different than the color ink (incongruent condition—e.g., “blue” printed in red ink) than when the letters spell the color in which the word is printed (congruent condition—e.g., “red” printed in red ink). For the purposes of examining the role of the callosum in this effect, the paradigm is modified so that a color word and color patch are displayed simultaneously and are either projected to the same or opposite visual fields. When the information is divided across the hemispheres, the Stroop effect is reduced or absent in split-brain patients (Zaidel & Rayman, 1994) and reduced in patients with agenesis of the corpus callosum (David, 1992) (despite the fact that a Stroop effect is found in unilateral conditions). These findings suggest that when information about the color word and color patch cannot be communicated between the hemispheres due to the lack of a commissural system, interference is reduced. In neurologically intact individuals in whom the commissures are intact, Stroop interference can occur even when items are positioned in opposite visual fields because transfer of information can occur via the callosum. The degree to which interhemispheric processing moderates the Stroop effect in neurologically intact individuals, however, has been somewhat confusing as some authors report a reduced Stroop effect when the color word and patch are located in the opposite rather than in the same visual field (e.g., David, 1992; Shenker, Dori, & Banich, 1994) whereas others find no difference (Weekes & Zaidel, 1996). Recently, we (Shenker & Banich, submitted) have obtained evidence to suggest that the degree to which dividing information across the visual fields reduces Stroop interference is dependent on how much attention the individual must devote to suppressing the color name.

Additional evidence for the role of the callosum in attentional functioning is provided by research with specific populations of individuals who have attentional disorders. One such group is patients with multiple sclerosis (MS). These patients, who suffer from a demyelinating disease that affects the cerebrum, have a reduction in myelination of the callosum as indexed on autopsy (Barnard & Triggs, 1974) and by MRI (Simon et al., 1986). Ana-

tomical reductions in callosal size observed on MRI in these patients appear to be indicative of poorer callosal function because patients with MS have difficulties in interhemispheric transfer (e.g., Jacobson, Deppe, & Murray, 1983; Lindeboom & Horst, 1988). These difficulties can sometimes be information specific, as difficulties in interhemispheric transfer of information in certain sensory modalities (e.g., visual) are related to the size of that region of the callosum which mediates transfer of that type of information (Rubens, Froehling, Slater, & Anderson, 1985; Pelletier et al., 1993). Attentional deficits, most notably in vigilance, have been observed in patients with multiple sclerosis (MS). For example, the ability of individuals with MS to sustain attention (as assessed by multiple measures) is correlated with the size of the callosum (as measured by MRI) (Rao et al., 1989). Moreover, this effect does not appear to be mediated by the general degree of compromise of the nervous system because the correlation remains significant even when the total amount of brain demyelination is considered.

Another clinical syndrome in which callosal functioning has been related to attention is closed head injury (CHI). Typically CHI is associated with diffuse axonal injury, and damage to the corpus callosum is a common consequence (Adams et al., 1989). In some cases it can be so severe as to lead to a callosal disconnection syndrome (e.g., Rubens, Geschwind, Mahowald, & Mastri, 1977). Of most importance, however, is that this callosal disconnection has attentional consequences. Two studies with 21 and 69 patients respectively, reported a specific suppression of information from the left ear in a dichotic listening paradigm, in which individuals must divide their attention across two competing stimulus streams, one directed to each ear (Levin, Grossman, Sarwar, & Meyers, 1981; Levin et al., 1989). Since verbal stimuli were utilized in these studies, specific suppression of left-ear information suggests an inability to transfer information from the right hemisphere to the left.

Another way of examining the relationship between callosal functioning and attention is to explore this issue developmentally. Myelination of the callosum continues from early childhood through the early teen years (Yakovlev & Lecours, 1967) if not later (Giedd et al., 1996) with the functional effect of reducing interhemispheric transfer time over 10 fold between the ages of 3 and 16 (Salamy, 1978). Thus, younger children can be considered akin to very "mild" split-brain patients, in that the callosum is not as functional as in adults. Recent studies suggest that the degree of callosal efficiency, as measured by an interhemispheric matching task and coordinated motor performance, is related to attention, more specifically vigilance in an item monitoring task (Rueckert, Sorensen, & Levy, 1994; Rueckert & Levy, 1996). Furthermore, children with difficulties in attentional processing, such as children with attentional deficit disorder, exhibit disruptions in callosal functioning (Hughes et al., 1982; Hynd et al., 1991). Hence, the evidence

from these many different populations all provide additional support for the idea that interhemispheric processing via the callosum affects attentional functioning.

### III. MECHANISMS BY WHICH INTERHEMISPHERIC INTERACTION MIGHT AFFECT ATTENTIONAL FUNCTIONING

If, as the foregoing discussion indicates, interhemispheric interaction via the callosum does indeed play a role in attentional processing, one must address the issue of what mechanism regulates such processing. At this point, any answers must be purely speculative.

It is highly unlikely that regulation of interhemispheric interaction occurs via a "homunculus" making decisions about attentional processing or that the callosum itself is the locus of such decision-making. At present, there are a number of possibilities, the viability of which cannot be differentiated at the present time. One possibility is that dynamic redistribution of processing *via the callosum* influences attentional processing in a manner akin to that observed in connectionist networks. Some connectionist models of attentional control have assumed that an attentional module modifies processing of other cognitive modules. For example, in a model of attentional effects in the Stroop task, Cohen (Cohen, Dunbar, & McClelland, 1990; Cohen, Servan-Schreiber, & McClelland, 1992) proposes that the adjustments of weights in the network between the attentional module and a color-identification module and a word reading module can replicate effects in the Stroop task. Thus, attentional effects are seen as emerging from the interactions among modules representing different types of information.

Analogously, one might imagine that the connections between the hemispheres via the callosum might act to modulate processing in each hemisphere and in some sense act as an "attention module." Thus, much the way in which connectionist networks readjust the weights between connections to better meet task demands or learn a task, the "connectivity" of the hemispheres could also be viewed as being a process that can dynamically undergo adjustment. Depending on task demands, the degree of connectivity would have different effects. Under attentionally demanding conditions, having high positive connection weights between the hemispheres would be useful, whereas for less demanding conditions, smaller or even negative connection weights would be useful.

Another possibility is that each hemisphere regulates the degree to which interhemispheric channels are open. For example, it may be that as long as a single hemisphere's capacity is not exceeded, the gate to information from the other hemisphere is closed. Such a possibility is raised by our findings (Banich & Passarotti, in preparation, a) indicating that when a single hemisphere receives two pieces of information which do not conflict (e.g., two items match in shape and they are the same color), information presented

to the opposite hemisphere does not affect performance.<sup>7</sup> Under this scenario there might be a locus of control, in that one hemisphere could "decide" that its processing capacity is starting to be exceeded, at which point the gate would be opened so that processing could be shunted to the other hemisphere. This suggestion is consistent with our findings that when a hemisphere receives two items that required attentional filtering (e.g., the items match in shape but are different in color, so that color must be filtered), information received by the opposite hemisphere influences performance. Thus, each hemisphere might individually regulate the degree of interchange or insulation with its partner. Such a model is compatible with the notion that each hemisphere has different attentional capabilities (and hence might want to open the gate at different times) as well as with some research suggesting that there may be an asymmetric exchange of information between the hemispheres (e.g., Braun & Daigneault, 1994; Marzi, Bisiacchi, & Nicoletti, 1991). Our results suggest that it is not advantageous to have the interhemispheric gate closed or it is more advantageous to have it open when task demands are high.

Such ideas about the mechanisms by which interhemispheric interaction influences attentional functioning will need to be explored in more detail, both with future empirical research and possibly with computational modeling as well. However, it is likely that future research will continue to provide converging evidence that interhemispheric interaction does indeed play an important role in attentional processing. If so, then our conceptualization of the network of neural structures that controls attention will need to be modified to make a place for inclusion of the corpus callosum.

## REFERENCES

- Adams, J. H., Doyle, D., Ford, I., Gennarelli, T. A., Graham, D. I., & McLellan, D. R. 1989. Diffuse axonal injury in head injury: definition, diagnosis and grading. *Histopathology*, **15**, 49-59.
- Banich, M. T., & Passarotti, A. (in preparation-a). *Interhemispheric interaction aids task performance under conditions of selective attention*.
- Banich, M. T., & Passarotti, A. (in preparation-b). *Parallel processing between the hemispheres increases processing capacity*.
- Banich, M. T., & Belger, A. 1990. Interhemispheric interaction: How do the hemispheres divide and conquer a task? *Cortex*, **26**, 77-94.
- Banich, M. T., Goering, S., Stolar, N., & Belger, A. 1990. Interhemispheric processing in left- and right-handers. *International Journal of Neuroscience*, **54**, 197-208.
- Banich, M. T., & Shenker, J. 1994. Investigations of interhemispheric processing: Methodological considerations. *Neuropsychology*, **8**, 263-277.

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<sup>7</sup> Another variation of this possibility is that the hemisphere does indeed receive the information, i.e., the gate is open, but has enough resources to suppress being influenced by that information.

- Banich, M. T., Passarotti, A., & Chambers, C. 1994. The role of the corpus callosum in attentional processing. Poster presented at the *Inaugural meeting of the Cognitive Neuroscience Society*, San Francisco, California.
- Barnard, R. O., & Triggs, M. 1974. Corpus callosum in multiple sclerosis. *Journal of Neurology, Neurosurgery and Psychiatry*, **37**, 1259–1264.
- Belger, A. 1993. *Influences of hemispheric specialization and interaction on task performance*. Unpublished doctoral dissertation. Department of Psychology, Univ. of Illinois.
- Belger, A., & Banich, M. T. *Costs and benefits of integrating information between the cerebral hemispheres: A computational perspective*. *Neuropsychologia*, in press.
- Belger, A., & Banich, M. T. 1992. Interhemispheric interaction affected by computational complexity. *Neuropsychologia*, **30**, 923–931.
- Braun, C. M. J., & Daigneault, S. 1994. Effects of a right hemifield advantage on crossed-uncrossed differentials in simple reaction time: Toward a new model of interhemispheric relay. *Acta Psychologica*, **85**, 91–98.
- Cohen, J. D., Dunbar, K., & McClelland, J. L. 1990. On the control of automatic processes: A parallel distributed processing model of the Stroop effect. *Psychological Review*, **97**, 332–361.
- Cohen, J. D., Servan-Schreiber, D., & McClelland, J. L. 1992. A parallel distributed processing approach to automaticity. *American Journal of Psychology*, **105**, 239–269.
- Corbetta, M., Miezin, F. M., Dobmeyer, S., Shulman, G. L., & Petersen, S. E. 1991. Selective and divided attention during visual discriminations of shape, color, and speed: Functional anatomy by positron emission tomography. *The Journal of Neuroscience*, **11**, 2383–2402.
- David, A. S. 1992. Stroop effects within and between the cerebral hemispheres: Studies in normals and aphasics. *Neuropsychologia*, **30**, 161–175.
- DeLacoste, M. C., Kirkpatrick J. B., & Ross, E. D. 1985. Topography of the human corpus callosum. *Journal of Neuropathology and Experimental Neurology*, **44**, 578–591.
- Dimond, S. J. 1976. Depletion of attentional capacity after total commissurotomy in man. *Brain*, **99**, 347–356.
- Dimond, S. J. 1979. Tactile and auditory vigilance in split-brain man. *Journal of Neurology, Neurosurgery, and Psychiatry*, **42**, 70–74.
- Ellenberg, L., & Sperry, R. W. 1979. Capacity for holding sustained attention following commissurotomy. *Cortex*, **15**, 421–438.
- Gazzaniga, M. S. 1987. Perceptual and attentional processes following callosal section in humans. *Neuropsychologia*, **25**, 119–133.
- Giedd, J. N., Rumsey, J. M., Castellanos, F. X., Rajapakse, J. C., Kaysen, D., Vaituzis, A. C., Vauss, Y. C., Hamburger, S. D., & Rapoport, J. L. 1996. A quantitative MRI study of the corpus callosum in children and adolescents. *Developmental Brain Research*, **91**, 274–280.
- Hellige, J. B., & Cox, P. J. 1976. Effects of concurrent verbal memory on recognition of stimuli from the left and right visual fields. *Journal of Experimental Psychology: Human Perception and Performance*, **2**, 210–221.
- Herdman, C. M., & Friedman, A. 1985. Multiple resources in divided attention: A cross modal test of independence of hemispheric resources. *Journal of Experimental Psychology: Human Perception and Performance*, **11**, 40–49.
- Holtzman, J. D., & Gazzaniga, M. S. 1982. Dual task interactions due exclusively to limits in processing resources. *Science*, **218**, 1325–1327.
- Holtzman, J. D., & Gazzaniga, M. S. 1985. Enhanced dual task performance following corpus commissurotomy in humans. *Neuropsychologia*, **23**, 315–321.
- Hughes, E. C., Weinstein, R. C., Gott, P. S., Binggeli, R., & Whitaker, K. L. 1982. Food

- sensitivity in attention deficit disorder with hyperactivity (ADD/HA): A procedure for differential diagnosis. *Annals of Allergy*, **49**, 276–280.
- Hynd, W., Semrud-Clikeman, M., Lorys, A. R., Novey, E. S., Elipulos, D., & Lyytinen, H. 1991. Corpus callosum morphology in attention deficit-hyperactivity disorder: Morphometric analysis of MRI. *Journal of Learning Disabilities*, **24**, 141–146.
- Jacobson, J. T., Deppe, U., & Murray, T. J. 1983. Dichotic paradigms in multiple sclerosis. *Ear and Hearing*, **4**, 311–317.
- Kahneman, D. 1973 *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.
- Kimchi, R., & Palmer, S. E. 1985. Separability and integrality of global and local levels of hierarchical patterns. *Journal of Experimental Psychology: Human Perception and Performance*, **11**, 673–688.
- Kinsbourne, M., & Hicks, R. E. 1978. Functional cerebral space: A model for overflow, transfer and interference effects in human performance: a tutorial review. In J. Requin (Ed.), *Attention and performance VII* (pp. 345–362). Hillsdale, NJ: Erlbaum.
- Knight, R. T., Hillyard, S. A., Woods, D. L., & Neville, S. J. 1981. The effects of frontal cortex lesions on event-related potentials during auditory selective attention. *Electroencephalography and Clinical Neurophysiology*, **52**, 571–582.
- Kramer, A. F., Coles, M. G. H., & Logan, G. D. 1996. *Converging operations in the study of visual selective attention*. Washington, DC: American Psychological Association Press.
- Kreuter, C., Kinsbourne, M., & Trevarthen, C. 1972. Are disconnected cerebral hemispheres independent channels? A preliminary study of the effect of unilateral loading on bilateral finger tapping. *Neuropsychologia*, **10**, 453–461.
- LaBerge, D. L. 1990. Attention. *Psychological Science*, **1**, 156–162.
- LaBerge, D., & Buchsbaum, M. S. 1990. Positron emission tomographic measurements of pulvinar activity during an attention task. *The Journal of Neuroscience*, **10**, 613–619.
- Levin, H. S., Grossman, R. G., Sarwar, M., & Meyers, C. A. 1981. Linguistic recovery after closed head injury. *Brain and Language*, **12**, 360–374.
- Levin, H. S., High, W. M., Williams, D. J., Eisenberg, H. M., Amparo, E., Guinto, F., & Ewert, J. 1989. Dichotic listening and manual performance in relation to magnetic resonance imaging after closed head injury. *Journal of Neurology, Neurosurgery and Psychiatry*, **52**, 1162–1169.
- Liederman, J. 1986. Subtraction in addition to addition: Dual task performance improves when tasks are presented to separate hemispheres. *Journal of Clinical & Experimental Neuropsychology*, **8**, 486–502.
- Liederman, J., Merola, J., & Hoffman, C. 1986. Longitudinal data indicate that hemispheric independence increases during early adolescence. *Developmental Neuropsychology*, **2**, 183–201.
- Lindeboom, J., & Horst, R. T. 1988. Interhemispheric disconnection in multiple sclerosis. *Journal of Neurology, Neurosurgery and Psychiatry*, **51**, 1445–1447.
- Luck, S. J., Hillyard, S. A., Mangun, G. R., & Gazzaniga, M. S. 1989. Independent attentional systems mediate visual search in split-brain patients. *Nature*, **342**, 543–545.
- Marzi, C. A., Bisiacchi, P., & Nicoletti, R. 1991. Is interhemispheric transfer of visuomotor information asymmetric? Evidence from a meta-analysis. *Neuropsychologia*, **29**, 1163–1177.
- Merola, J. L., & Liederman, J. 1985. Developmental changes in hemispheric independence. *Child Development*, **56**, 1184–1196.
- Merola, J. L., & Liederman, J. 1990. The effect of task difficulty upon the extent to which performance benefits from between-hemisphere division of inputs. *International Journal of Neuroscience*, **51**, 35–44.

- Mesulam, M.-M. 1981. A cortical network for directed attention and unilateral neglect. *Annals of Neurology*, **10**, 309–325.
- Navon, D. 1977. Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, **9**, 353–383.
- Nelson, M. E., & Bower, J. M. 1990. Brain maps and parallel computers. *Trends in Neuroscience*, **13**, 403–408.
- Pardo, J. V., Pardo, P. J., Janer, K. W., & Raichle, M. E. 1990. The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Science*, **87**, 256–259.
- Passarotti, A., & Banich, M. T. (in preparation). *A generalized role of interhemispheric interaction under attentionally-demanding conditions: Evidence from the auditory and tactile modalities.*
- Pelletier, J., Habib, M., Lyon-Caen, O., Salamon, G., Poncet, M., and Khalil, R. 1993. Functional and MRI correlates of callosal involvement in multiple sclerosis. *Archives of Neurology*, **50**, 1077–1082.
- Posner, M. I., Inhoff, A. W., Friedrich, F. J., & Cohen, A. (1987). Isolating attentional systems: A cognitive-anatomical analysis. *Psychobiology*, **15**, 107–121.
- Rao, S. M., Bernardin, L., Leo, G. J., Ellington, L., Ryan, S. B., & Burg, L. S. 1989. Cerebral disconnection in multiple sclerosis: relationship to atrophy of the corpus callosum. *Archives of Neurology*, **46**, 918–920.
- Rayman, J., & Zaidel, E. 1991. Rhyme and the right hemisphere. *Brain and Language*, **40**, 89–105.
- Robertson, L., & Lamb, M. R. 1991. Neuropsychological contributions to theories of part/whole organization. *Cognitive Psychology*, **23**, 299–330.
- Robertson, L. C., Lamb, M. R., & Knight, R. T. 1988. Effects of lesions of temporal-parietal junction on perceptual and attentional processing in humans. *The Journal of Neuroscience*, **8**, 3757–3769.
- Robertson, L. C., Lamb, M. R., & Zaidel, E. 1993. Interhemispheric relations in processing hierarchical patterns: Evidence from normal and commissurotomy subjects. *Neuropsychology*, **7**, 325–342.
- Rubens, A. B., Geschwind, N., Mahowald, M. W., & Mastri, A. 1977. Post-traumatic cerebral hemispheric disconnection syndrome. *Archives of Neurology*, **34**, 750–755.
- Rubens, A. L., Froehling, B., Slater, G., & Anderson, D. 1985. Left ear suppression on verbal dichotic tests in patients with multiple sclerosis. *Annals of Neurology*, **18**, 459–463.
- Rueckert, L., & Levy, J. 1996. Further evidence that the callosum is involved in sustaining attention. *Neuropsychologia*, **34**, 927–935.
- Rueckert, L., Sorenson, L., & Levy, J. 1994. Callosal efficiency is related to sustained attention. *Neuropsychologia*, **32**, 159–173.
- Rugg, M. D., Lines, C. R., & Milner, A. D. 1984. Visual evoked potentials to lateralized visual stimuli and the measurement of interhemispheric transmission time. *Neuropsychologia*, **22**, 215–225.
- Salamy, A. 1978. Commissural transmission: Maturation changes in humans. *Science*, **200**, 1409–1411.
- Sergent, J. 1990. Furtive incursions into bicameral minds: Integrative and coordinating role of subcortical structures. *Brain*, **113**, 537–568.
- Shenker, J. I., Dori, E., & Banich, M. T. 1994. Hemispheric contributions to facilitation and inhibition in the Stroop paradigm. Paper presented at the *Annual Meeting of the International Neuropsychological Society*, Cincinnati, Ohio.

- Shenker, J. I., & Banich, M. T. (submitted). *The modulation of attentional capacity in the Stroop task by communication between the cerebral hemispheres.*
- Simon, J. H., Holtas, S. L., Schiffer, R. B., Rudick, R. A., et al. 1986. Corpus callosum and subcallosal-periventricular lesions in multiple sclerosis: detection with MR. *Radiology*, **160**, 363–367.
- Treisman, A. M., & Gelade, P. A. 1980. A feature integration theory of attention. *Cognitive Psychology*, **12**, 97–136.
- Teng, E. L., & Sperry, R. W. 1973. Interhemispheric interaction during simultaneous bilateral presentation of letters and digits in commissurotomed patients. *Neuropsychologia*, **11**, 131–140.
- Teng, E. L., & Sperry, R. W. 1974. Interhemispheric rivalry during simultaneous bilateral task presentation in commissurotomed patients. *Cortex*, **10**, 111–120.
- Van Kleeck, M. H. (1989). Hemispheric differences in global versus local processing of hierarchical visual stimuli by normal subjects: New data and a meta-analysis of previous studies. *Neuropsychologia*, **27**, 1165–1178.
- Weissman, D. H., & Banich, M. T. (submitted). *Global-local interference modulated by interaction between the hemispheres.*
- Weekes, N. Y., Carusi, D., & Zaidel, E. 1997. Interhemispheric relations in hierarchical perception: A second look. *Neuropsychologia*, **35**, 37–44.
- Weekes, N. Y., & Zaidel, E. 1996. The effects of procedural variations on lateralized Stroop effects. *Brain & Cognition*, **31**, 308–330.
- Wickens, C. D. & Liu, Y. 1988. Codes and modalities in multiple resources: A success and a qualification. *Human Factors*, **30**, 599–616.
- Zaidel, E., & Rayman, J. 1994. Interhemispheric control in the normal brain: Evidence from redundant bilateral presentations. In C. Umiltà, & M. Morris Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing*, Cambridge, MA: The MIT Press.