Neural Gate Keeping: The Role of Interhemispheric Interactions in Resource Allocation and Selective Filtering

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The corpus callosum has been proposed to contribute to attention by modulating resource allocation between the hemispheres and filtering interhemispheric signal transmission (M. T. Banich, 1998). The resource allocation hypothesis predicts that interhemispheric interactions become more advantageous with increasing resource demands. The selective filtering hypothesis predicts that interhemispheric interactions become less advantageous as filtering requirements increase. The authors tested both predictions by comparing within- and across-hemisphere letter matching under dual-task (Experiment 1) and selective attention conditions (Experiment 2). Task-specific resource demands (i.e., letter processing load) alter the bihemispheric advantage, but the general demand imposed by an unrelated secondary task does not. Filtering requirements influenced the advantage from interhemispheric interactions, providing new evidence for the role of the corpus callosum in selective attention.

The corpus callosum is the largest and most prominent commissure interconnecting the left and right cerebral hemispheres. Although the neuroanatomical properties of this interhemispheric tract have been characterized in extensive detail (Aboitiz, Scheibel, Fisher, & Zaidel, 1992; Alexander & Warren, 1988; de Lacoste, Kirkpatrick, & Ross, 1985; Innocenti, 1986; Naito, Miyakowa, & Ito, 1971; Pandya & Seltzer, 1986), the precise functions of the corpus callosum are less clearly defined. Complete transection of the corpus callosum for the treatment of epilepsy yields two virtually independent spheres of cognition capable of perceiving, processing, and selecting responses in parallel and with minimal interference (see Reuter-Lorenz, 2003, for a review). Thus, in the broadest sense the corpus callosum mediates virtually all interactions required for an integrated mind. Indeed, in the last several decades great strides have been made toward defining the sensory, motor, linguistic, and mnemonic information relayed between the left and right hemispheres by way of the corpus callosum (Banich, 1998; Corballis, 1995; Gazzaniga, 2000; Hugdahl, 2000; Reuter-Lorenz & Miller, 1998; Saron, Foxe, Simpson, & Vaughan, 2003).

The effort to identify the functions of the corpus callosum derives from a basic interest in understanding the evolutionary advantages bestowed by the hemispheric organization of the brain. What are the unique processing benefits conferred by a design that necessitates communication via this great forebrain commissure? One recurring answer is that the hemispheric organization of the brain and the attendant callosally mediated interactions permit the development of specialized neural systems and capacities that can function and coexist with minimal interference. By this view, the corpus callosum modulates information flow and insulates the operations of lateralized processors. Contrarily, lateralized processors typically comprise functional systems whose components are distributed, anteriorly and posteriorly, left and right, across the brain. Some processors are highly specialized, residing in one hemisphere and not the other, as is the case with particular language-related modules (Baynes, Eliassen, Lutsep, & Gazzaniga, 1998). In other cases there appears to be more overlap and redundancy in the functionality of left and right hemisphere processors (Reuter-Lorenz & Miller, 1998). In both cases the corpus callosum is required to orchestrate the dynamic recruitment and integrated functioning of differently lateralized processors.[1]

Based on work from her own and other labs, Banich (1998) recently conceptualized these aspects of callosal function in terms of attentional control. She proposed that interhemispheric interactions contribute to attentional control in two specific complimentary but different ways. First, under certain task conditions, interhemispheric interactions modulate the quantity of neural resources that are available to perform a task. To the extent that each hemisphere has competence on a task, processing can be divided between them and conducted in parallel. There is a cost to coordinating the operations of separate, lateralized processors, as evidenced by the well established fact that observers are slower to respond to a left visual field flash when using their right hand than when using their left hand and likewise for a right visual field flash (Bashore, 1981; Clarke & Zaidel, 1989; Jeeves & Moes, 1996; Milner & Rugg, 1989). However, when the resource demands of a task are high (or during the completion of two conflicting tasks)

[1] Although the goal is to understand the functions of the corpus callosum, we acknowledge that this structure is a white matter pathway whose role stems from the processing operations mediated by the cortical gray matter that gives rise to the interhemispheric fibers. Indeed, the functions of the interhemispheric interactions that are mediated by these callosal fibers are the actual focus of the field and of our investigation.

this coordination cost is outweighed by the increased capacity conferred by engaging two parallel processors (Belger & Banich, 1992; Liederman & Meehan, 1986; Merola & Liederman, 1990). Second, Banich proposed that under different task conditions, callosally mediated interactions also have the potential to gate or filter distracting and irrelevant information, thereby implementing attentional selection (for a similar idea with respect to insulating concurrent dissimilar processes, see Liederman, 1986). The experiments described in this article were designed to test these two proposals about the attentional contributions of the corpus callosum. Before describing these experiments, we review resource allocation and selective attention as they relate to the hypothesis that interhemispheric interactions contribute to these functions.

The Corpus Callosum and Resource Allocation

There is a growing body of evidence to support a role for callosally mediated interhemispheric interactions in resource allocation (Banich & Belger, 1990; Belger & Banich, 1992; Dimond, 1976; Herdman & Friedman, 1985; Liederman, 1998). Critical evidence comes from behavioral studies that have compared accuracy and reaction time performance under conditions that require interhemispheric processing versus those that do not (see Banich, 1998, for a review). Banich and her colleagues developed a model task that has been used extensively in the visual modality, and it has been applied more recently to the auditory and tactile modalities as well (Passarotti, Banich, Sood, & Wang, 2002). In the visual task, the display contains a single letter in the lower half of the screen. That target letter is positioned to the left or right of a central fixation point on which participants are instructed to gaze. Probe letters appear in the upper half of the display screen, an equal number in each visual field. The participant's task is to decide whether the target letter matches any of the probes in the upper row(s). The critical manipulation involves the relative locations of the target and the matching probe. On within-field trials, the target and matching probe appear on the same side of the central fixation point and are projected to the same hemisphere. Under these conditions, match processing is assumed to be unilateral because the critical items can be encoded and a match decision can be made without interactions between the two hemispheres.

On across-field trials, interhemispheric interactions are essential because the target letter appears in one visual field and the matching probe item appears in the other (e.g., Seymour, Reuter-Lorenz, & Gazzaniga, 1994). Therefore, each of the two critical items is encoded by a different hemisphere, and the products must be combined for a match decision to be reached. Across-field trials thus require bihemispheric processing.

Variations in this basic paradigm can be used to determine the conditions under which bihemispheric processing is advantageous. For example, the number of probe items can vary to manipulate the number of comparisons that need to be performed to determine the presence or absence of a match. Also, the matching criterion can vary so that a match is based on the physical identity (PI) of the letters, as illustrated in Figure 1A and 1B, or on the abstract identity (i.e., name identity, NI) as in Figure 1C. A number of studies have now established that on relatively easy tasks, such as the three-PI task just discussed, matching performance is superior for within-field trials compared to across-field trials. However, as task difficulty increases, by adding more probes or requiring a more abstract match, there is an increasing advantage on across-field trials compared with within-field trials (Banich & Belger, 1990; Banich & Karol, 1992; Reuter-Lorenz, Stanczak, & Miller, 1999). Banich and Belger (1990) argued that this shift toward a bilateral processing advantage occurs because each lateralized pool is limited in capacity, and across-field trials increase capacity by recruiting processing resources from both hemispheres to meet task demands. When tasks are difficult, the benefit from engaging bilateral pools of resource outweigh the cost incurred by the need to coordinate processing operations between the two hemispheres. For easier tasks, unilateral resources are sufficient, so the cost of interhemispheric interactions is evident by poorer performance on across-field trials.

Critical to Banich's proposal relating interhemispheric interactions to resource allocation is the notion of task demand. Certainly easier tasks are less demanding, but Banich and colleagues proposed that the advantage from bihemispheric processing depends on the computational complexity of the task rather than its sheer difficulty (Belger & Banich, 1992). According to this view, adding more probe letters or requiring matches based on identity increases
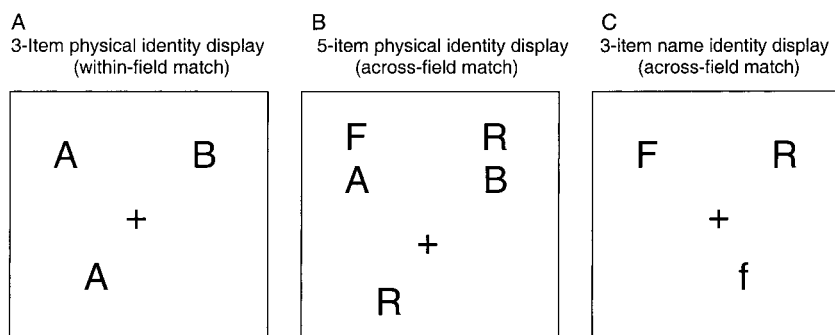
Figure 1. Sample displays illustrating within-hemisphere and across-hemisphere matches across three levels of task difficulty. The target letter always appeared at the bottom of the display, and the probe letters were always in the upper rows of the display. In the physical identity match trials (A and B), the target letter physically matched one of the probes (in this example, A-A and R-R, respectively). In the name identity match trials (C), the target had the same name as one of the probes (in this example, f-F).

the number of computations that must be performed on the letters, which increases the computational complexity of the task. Bihemispheric processing enables these computations to be performed in parallel thereby meeting the resource demands of complex tasks.

What remains to be determined, however, is the specificity of resource demands that elicit a bihemispheric advantage. That is, do increased resource requirements of any type promote a bihemispheric processing advantage? The tradition of attention research on resource theory is instructive on this point (e.g., Kahneman, 1973). The limitations on processing imposed by limitations in resources have traditionally been studied using a dual-task (DT) approach. Two tasks that draw on a common pool of resources will interfere with one another when they are performed concurrently. Tasks that draw on different resource pools can be executed with minimal interference. Indeed, attention research and neuropsychological research have an extensive history of applying the DT method to determine the structural and functional overlap of different cognitive operations (Barnes, Nelson, & Reuter-Lorenz, 2001; Granholm, Asarnow, & Marder, 1996; Greenwald, 1972; Hellige, Bloch, & Taylor, 1988; Kinsbourne & Hicks, 1978; Liederman, 1986; Logie, Gilhooly, & Wynn, 1994; Pashler, 1994; Pashler & O'Brien, 1993; Schumacher et al., 2001; Welford, 1952).

In Experiment 1, we used the DT method to better define the type of resource requirements (or task demands) that promote bihemispheric processing. The effects of adding a secondary task are compared with the effects of increasing the computational complexity of the letter matching decision. Like increasing computational complexity, if the addition of a secondary task increases the bihemispheric advantage, then we would conclude that interhemispheric interactions modulate the availability of general resources. Finding that the dual task does not alter the hemispheric processing advantage, despite a clear increase in overall task difficulty, would support the view that interhemispheric interactions modulate the availability of specific resources—in this case, resources associated specifically with letter processing.

The Corpus Callosum and Selective Filtering

It has also been proposed that by modulating interhemispheric interactions, concurrent inputs and/or processes can be insulated from each other (Banich, 1998; Liederman, 1986) and irrelevant information can be filtered (Weissman & Banich, 1999; for a review, see Chiarello & Maxfield, 1996). If the corpus callosum can insulate irrelevant or conflicting processes, then distributing conflicting tasks to different hemispheres should improve performance relative to conditions that mitigate this division of labor. For example, Merola and Liederman (1985, 1990) reported that when two conflicting inputs are presented in opposite visual fields (e.g., letters requiring different directional rotations to achieve upright), performance is better than when both inputs go to the same hemisphere. Note, however, that in these studies the advantage in the bilateral presentation condition could arise from several different sources. In the unilateral conditions, interference could arise at encoding, during task processing, or during response selection (for similar arguments, see Banich, 1998). Likewise, a bilateral advantage could result if the resource demands of these tasks are more optimally satisfied compared with the unilateral condition (see also Weissman & Banich, 1999; and Shenker &

Banich, 1999, as cited in Weissman & Banich, 1999). Therefore, the implications of these results for attentional selection per se are unclear.

Our approach in Experiment 2 is in the tradition of selective filter theories of attention (Broadbent, 1958; Deutsch & Deutsch, 1963; Kahneman, Treisman, & Burkell, 1983; for a review see Van der Heijden, 1992). The need to filter irrelevant input has a cost on performance (Kahneman et al., 1983). For instance, target identification is significantly delayed in the presence of irrelevant visual stimuli (black disks, differently colored or positioned items, etc.; B. A. Eriksen & C. W. Eriksen, 1974; C. W. Eriksen & Hoffman, 1972; C. W. Eriksen & Schultz, 1978). This increase in performance latency has been referred to as a filtering cost. We reasoned that if the corpus callosum can insulate one hemisphere from irrelevant information presented to the other, then bihemispheric processing would become decreasingly advantageous as the need to filter increases. Specifically, when distractors are presented bilaterally, as the interference they produce increases, performance on across-field matches will suffer disproportionately because interhemispheric interactions required on these trials introduces distraction from both visual fields. Likewise, within-field match trials will be advantageous because the hemisphere processing the match is insulated from the distraction presented in the opposite visual field.

Experiment 2 tested the filtering function of callosally mediated interhemispheric interactions by presenting bilateral irrelevant distractors that varied in categorical similarity and spatial discriminability from the relevant probes. To the extent that the corpus callosum can filter irrelevant information, unilateral processing (within-field, within-hemisphere matches) should be increasingly advantageous as the requirement for filtering increases.

Experiment 1

In Experiment 1, we aimed to clarify the contribution of interhemispheric interactions to resource allocation by introducing the kind of secondary task that has been shown to produce substantial interference effects and has been used to simulate in younger adults the resource limitation thought to be associated with cognitive aging (McDowd, 1986; McDowd & Craik, 1988; Rabinowitz, Craik, & Ackerman, 1982; Rieck, Ogden, & Anderson, 1980).

Experiment 1 increased resource demands by requiring tone counting during letter matching performance. Our goal was to determine if the higher resource demand in the dual-task condition would shift the within-field advantage that is typical of the three-letter PI task toward an across-field advantage. If interhemispheric interactions modulate the availability of general resources, then the increased demand imposed by the DT requirement should be met more effectively in the across-field than the within-field match condition. The absence of a shift toward a bihemispheric advantage, even in the face of increased difficulty, would suggest that specificity in resource demands and computational complexity per se determine the optimality of bihemispheric processing.

Method

Participants

Twenty participants (*M* age = 19.1 years) were recruited through the introductory psychology subject pool at the University of Michigan. All

participants were right-handed and had normal or corrected-to-normal vision. Participants received course credit for their participation.

Apparatus

A Macintosh PowerPC with PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) was used for stimulus presentation and data acquisition. Participants sat with their chin in a headrest to ensure a constant viewing distance of 57 cm.

Design

Matching tasks. Two letter matching tasks varying in computational complexity were used under both the within- and across-hemisphere conditions: three-PI and three-NI. In both tasks, the stimulus displays had the same spatial arrangement. The target letter appeared 1.4° below and 1.4° to the left or right of the central fixation cross, and the two probe letters appeared 1.4° above the fixation cross and 2.8° to the left or right of the fixation cross (one letter in each visual field). Each letter subtended a maximum of 0.85° horizontally and 1.2° vertically. Targets and probes were chosen randomly from the following set of letters: A, B, D, F, G, H, M, N, R, S, and T. In the three-PI task, all letters were uppercase. In the three-NI task, the target was lowercase and the probes were uppercase. The targets were presented randomly and with equal probability in the left or right visual field. On half of the trials, the target matched one of the probes; on the other half, there was no match. When the target matched a probe, the matching probe was equally likely to appear in the same visual field as the target (a within-field match) or in the visual field opposite to the target (an across-field match). The participants were required to press the space bar if the target letter matched one of the probe letters above the cross. If no match occurred, responses were to be withheld. The reaction time and accuracy of match responses were recorded.

Tone counting and DT. The secondary task required tone counting, and it was performed alone and concurrently with the three-PI task. Each trial contained a sequence of 11 tones that started 200 ms after the start of the trial. Each tone lasted approximately 100 ms, and the intertone interval was 200 ms. On DT trials, the tones were synchronized to occur simultaneously with the onset of the letter array. During the tone counting alone task, the participants were still instructed to focus their eyes on the fixation cross while they viewed a series of three-PI trials. Similar in design to the three-PI task, for half of the trials the target matched one of the probes; for the other half, the target did not match the probe. Nonetheless, the participants were instructed to attend only to the auditory signals and to ignore the letters while maintaining fixation. The timing of all trial events was identical to the DT condition. The tone series included seven or eight high-pitched tones and three or four low-pitched tones. The 3 or 4 low-pitched tones occurred in quasirandom positions within the 11-tone sequence.[2] If three low tones occurred, participants pressed the *z* key, and if four low tones occurred, they pressed the *x* key.

In the DT condition, participants performed the three-PI task concurrently with the tone counting task. They were instructed to give their match response first and then to indicate the number of target tones. Participants were instructed to perform both tasks as well as possible and not to favor one task over the other. When the three-PI and three-NI letter matching tasks were performed alone, 11 high tones were presented to produce similar sensory conditions across tasks and to isolate the effects of DT demands per se. Participants were told that the tones were irrelevant to their task.

Procedure

Participants were instructed to focus on a central fixation cross during each trial. Trials began with a blink of the fixation cross and a warning beep. After a 500-ms pause, the letter array appeared for 200 ms. Partic-

ipants were instructed to respond only if the target matched one of the probes and to refrain from responding if it did not (a go/no-go procedure). On match trials, they were to press the space bar with their right index finger as quickly as possible without compromising accuracy. The response interval was 2 s. Each task (three-PI, three-NI, tone counting alone, and DT) contained one practice block and three experimental blocks. All blocks consisted of 64 trials. The order of the four tasks was counterbalanced across participants.

Results

Tone Counting

An analysis of variance (ANOVA) was computed for tone counting accuracy with the within-subject factor of Task (tone counting alone and DT). The analysis revealed a significant main effect, $F(1, 19) = 7.25$, $p < .05$. Counting accuracy was lower in the DT condition (DT = 94.9% correct and tone counting alone = 96.7% correct). The small but significant drop in accuracy in the DT reflects its increased difficulty compared with tone counting alone.

Letter Matching

To analyze response latencies, outliers were trimmed using the following two-step procedure. First, response times faster than 200 ms were designated as outliers and removed (less than 1% of the data). For each participant an overall mean and standard deviation were then calculated for each task. Responses exceeding 2.5 SDs were then eliminated (we cut approximately 2% of all responses). The accuracy analyses presented are based only on correct match trials that meet these latency criteria.[3]

Separate repeated measures ANOVAs were computed for the latency and accuracy data with the within-subject factors of Task (three-PI, three-NI, and DT) and Presentation Condition (within field and across field).

Reaction time. As shown in Figure 2, the significant increase in reaction time for the DT relative to the three-PI task indicates that our manipulation was effective in increasing letter matching difficulty. This was confirmed statistically by a significant main effect for task, $F(2, 38) = 44.18$, $p < .001$, in which tasks were significantly different from each other (all ps $< .001$). The analysis also showed a main effect for presentation condition

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[2] To ensure that participants listened attentively to the tones and counted them through the entire trial, we used a quasirandom ordering. The low tones occurred with the following constraints: (a) The first low tone occurred as the second or third tone in the whole sequence; (b) the second and/or third low tone (the second tone in a 3 low-tone sequence or the second and third tones in a 4 low-tone sequence) occurred in the sequence as the fifth, sixth, seventh, or eighth tones; and (c) the final tone occurred as the tenth or eleventh tone in the sequence.

[3] No-go trials, in which no letter match was present, were analyzed separately because they cannot provide information about within- or across-field advantages. Performance on these trials was virtually at ceiling, with errors (i.e., false alarms) occurring on less than 1% of the trials. Errors followed the same general pattern as the reaction times and accuracy for correct matches, such that the three-NI task produced the poorest performance (three-NI = 2.4% errors, three-PI = 1% errors, and DT = 0.8% errors), $F(2, 38) = 18.83$, $p < .001$.
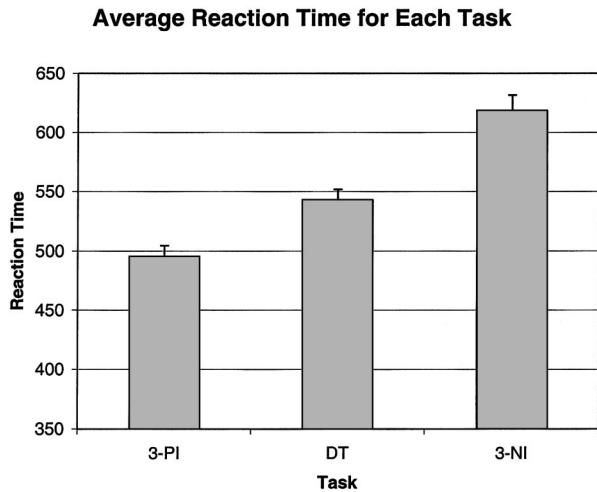
Average Reaction Time for Each Task

Figure 2. Overall reaction time (RT) for each task (+*SE*). PI = physical identity; DT = dual task; NI = name identity.

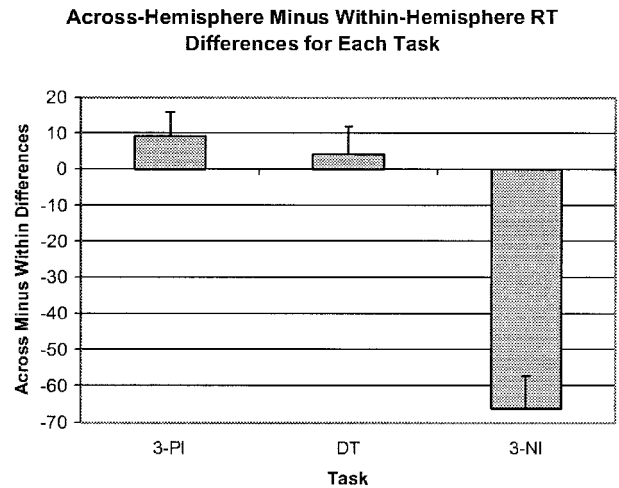**Across-Hemisphere Minus Within-Hemisphere RT Differences for Each Task**

Figure 3. Reaction time (RT) differences for each task (+*SE*). A positive value indicates a within-hemisphere advantage, whereas a negative score indicates an across-hemisphere advantage. PI = physical identity; DT = dual task; NI = name identity.

indicating that across-field matches (543.44 ms) were faster than within-field matches (560.93 ms), $F(1, 19) = 9.23$, $p < .01$. All means appear in Table 1.

Most important, there was a significant Task × Condition interaction, $F(2, 38) = 42.98$, $p < .001$. This interaction indicates that the relative advantage of the within-field or across-field conditions depended on the task. It is clearly illustrated by subtracting the within-field (i.e., within-hemisphere) reaction time from across-field (i.e., across-hemisphere) reaction time to obtain a difference score that indicates the hemispheric processing advantage. Positive differences indicate a within-hemisphere or unilateral advantage, and negative differences indicate an across-hemisphere or bihemispheric advantage. As shown in Figure 3, the within-hemisphere advantage is equivalent for the three-PI task and the DT, $F(1, 19) = 0.30$, $p > .5$, whereas a clear across-hemisphere advantage emerges for the three-NI task that is significantly different from the three-PI and DT advantages, $F(1, 19) = 68.73$, $p < .001$, and $F(1, 19) = 59.89$, $p < .001$, respectively. Thus, despite the increased difficulty of the DT compared with the three-PI condition, there was no alteration in the unilateral processing advantage observed in the three-PI task.

Accuracy. As shown in Table 2, there were minimal variations in accuracy across the three tasks. An ANOVA revealed that the overall accuracy levels did not reliably differ across the three tasks and that there was no overall effect of presentation condition. Only the Task × Condition interaction was significant, $F(2, 38) = 6.46$, $p < .01$. Presentation condition had a small but reliable effect only in the DT, producing a slight within-hemisphere advantage like that observed in the reaction time data, $F(1, 19) = 7.15$, $p < .05$.

Discussion

Experiment 1 demonstrates that different methods of manipulating task difficulty, and presumably resource demands, have different effects on hemispheric recruitment. One method varied the depth or computational complexity of letter processing per se by requiring that letter representations be recoded from their physical form to their abstract identity. The requirements of this task were met more efficiently when the critical matching items could be processed by opposite hemispheres compared with when

Table 1

Average Reaction Time and Standard Error Scores in Each Letter Matching Task Under Within-Hemisphere and Across-Hemisphere Conditions, and the Across Minus Within Difference for Each Task

Task	Three-PI task		Three-NI task		DT	
	M	*SE*	*M*	*SE*	*M*	*SE*
Within	490.77	13.72	651.19	19.78	540.83	14.05
Across	500.10	12.16	585.07	17.59	545.14	11.01
Combined	495.44	9.12	618.13	13.66	542.98	8.87
Across − Within	9.33		−66.12		4.31	

Note. PI = physical identity; NI = name identity; DT = dual task.

Table 2

Average Accuracy and Standard Error Scores in Each Letter Matching Task Under Within-Hemisphere and Across-Hemisphere Conditions, and the Across Minus Within Difference for Each Task

Task	Three-PI task		Three-NI task		DT	
	M	*SE*	*M*	*SE*	*M*	*SE*
Within	96.4	0.8	95.6	0.8	98.1	0.5
Across	97.3	0.6	96.7	0.7	96.6	0.6
Combined	96.8	0.5	96.1	0.5	97.4	0.4
Across − Within	0.9		1.1		−1.5	

Note. PI = physical identity; NI = name identity; DT = dual task.

a single hemisphere processed both critical items. Bihemispheric processing met the increased resource demands imposed by this difficulty manipulation. By contrast, the addition of the secondary task, which clearly made letter matching performance more difficult, had no effect at all on the bihemispheric advantage. This result demonstrates an important boundary condition for defining the kinds of demands that alter hemispheric cooperation. In our case, we can infer that tone counting and letter matching interfered with one another at a stage of processing when efficiency was not improved by the across-field presentation of the critical letters. Presumably, this would be a later stage of processing associated with response selection or response execution.

These results suggest that the computational complexity of the letter matching decision per se is what drives the benefit associated with bihemispheric processing in this paradigm. If processing information with both hemispheres increased the availability of resources generally, then we would have expected that any manipulation of task difficulty, especially one designed to increase resource demand, would render bihemispheric processing advantageous. Instead, the results suggest that the resources recruited by interhemispheric interactions are quite specific and related to an optimal division of labor between the two sides of the brain.

Experiment 2

In Experiment 2, we examined how the filtering requirements of a task affect the hemispheric processing advantage. Our strategy was to manipulate the degree of visual distraction in a letter matching task by including irrelevant information in the stimulus display. If interhemispheric interactions permit cross talk between lateralized processing operations, then under conditions of distraction minimizing such interactions should insulate and benefit lateralized processing. Accordingly, as the need for selective filtering increases, we would expect interhemispheric interactions to become less advantageous. This view predicts that the relative advantage of unilateral processing should increase with increasing distraction and that bihemispheric processing should be less advantageous. Note that the selective filtering function of interhemispheric interactions predicts an effect opposite to that of the resource allocation function. To test the filtering function in Experiment 2, two of the five items in the display are designated as irrelevant. To test the resource allocation function, the number of relevant items is increased to five.

Method

Participants

Twenty participants (*M* age = 19.0) were recruited through the introductory psychology subject pool at the University of Michigan. All participants were right-handed and had normal or corrected-to-normal vision. Participants received course credit for their participation.

Apparatus

As in Experiment 1, a Macintosh PowerPC with PsyScope software (Cohen et al., 1993) was used for stimuli presentation and data acquisition. Participants sat with their chin in a headrest to ensure a constant viewing distance of 57 cm.

Design

This experiment included five variants of the PI letter matching task: three with distractors and two without. The three-PI and five-PI tasks, both without distractors, were included to test the resource allocation function of interhemispheric interactions and to provide baseline measures of the unilateral versus bihemispheric processing advantages typically associated with 3- and 5-item displays, respectively. The effects of distractors were compared to the direction and magnitude of these baselines (discussed next).

In all tasks the target letter appeared 1.4° below and 1.4° to the left or right of the central fixation cross. In the three-item displays, two probe letters appeared 1.4° above the fixation cross and 2.8° to the left or right of the fixation cross (one letter in each visual field). In the five-item tasks, the four probe characters appeared in two rows (0.87° and 1.9° above the fixation cross), with each character 2.8° left or right of the fixation cross. Each character subtended a maximum of 0.85° horizontally and 1.2° vertically. Targets and probes were chosen randomly from the following set of letters: A, B, D, F, G, H, M, N, R, S, and T.

As in Experiment 1, targets appeared randomly and with equal probability in the left or right visual field, with matching probes occurring on 50% of the trials. Matching probes were equally likely to appear in the same visual field as the target (a within-hemisphere match) or in the visual field opposite to the target (an across-hemisphere match).

In the three-PI and five-PI tasks, all letters were uppercase and the target letter below the fixation point could physically match one of the probe letters above the fixation point. Thus, all of the letters in the three-PI and five-PI tasks were relevant. For the three distracting tasks, the distracting information varied in category similarity and/or in spatial predictability. In the fixed symbol (FS) task, two symbols (chosen from a set of 11 possible distractor symbols: Ω, ξ, ⊕, ℑ, ϑ, ϕ, Φ, Ψ, &, Θ, Ξ) served as distractors and always appeared directly above the two-letter probes. Thus, the FS task was a five-item task in which two of the probe items were categorically and spatially irrelevant. In the fixed letter (FL) tasks, four uppercase letters appeared above the fixation point and the target letter only had the possibility of matching one of the two lower probes. The lower two probes were taken from different lists than the two upper probes, such that the target list never matched the upper letter lists on a given trial. In addition, participants were instructed that the upper two letters would never match the target. Thus, the FL task was a five-item task in which the upper row of probe letters was categorically relevant but spatially irrelevant to the task. Finally, the variable symbol (VS) task was the same as the FS tasks, with the exception that the position of the probes and symbols varied. The vertical location of the distracting information was randomized, and this spatial uncertainty was expected to evoke the greatest filtering demand. Sample stimulus displays for these three tasks are shown in Figure 4.

Procedure

Participants were instructed to focus on the central fixation cross throughout each trial. At the beginning of each trial, the cross appeared and a warning tone sounded. After a 500-ms pause, the target and probe array appeared for 200 ms. Participants were asked to press the space bar with
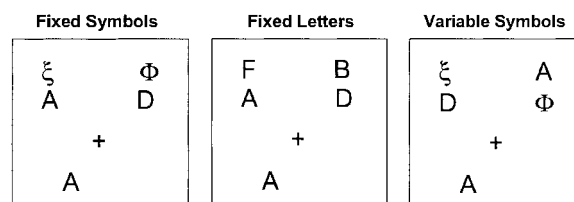

Fixed Symbols	Fixed Letters	Variable Symbols
ξ Φ	F B	ξ A
A D	A D	D Φ
+	+	+
A	A	A

Figure 4. Samples for each of the tasks with distracting information.

their right index finger if the target item matched one of the probe items and to withhold responses if no match was present. Each task contained one practice block of 32 trials and three experimental blocks of 64 trials. The order of the five tasks was counterbalanced across participants.

Results and Discussion

The latency data were trimmed and analyzed according to the procedure described in Experiment 1.[4] Separate repeated measures ANOVAs were computed for the latency and accuracy data with the within-subject factors of Task (three-PI, five-PI, FS, FL, and VS) and Presentation Condition (within field and across field).

Reaction Time

There was a significant main effect for Task, $F(4, 76) = 10.97$, $p < .001$. As expected and shown in Figure 5, simple effect analyses revealed that the five-PI task was associated with longer reaction times than the three-PI task, $F(1, 19) = 23.60$, $p < .001$. As discussed previously, longer latencies are presumed to reflect the increased computational demands imposed by the four versus two relevant probes. Also evident in Figure 5 is a stepwise increase in reaction time for the distraction conditions, reflecting the difficulty due to distraction and presumably the requirement for selective filtering imposed by each distractor type. Compared to the three-PI task, the FS task did not differ in response latency, $F(1, 19) = 0.02$, $p > .8$; FL latencies were marginally longer, $F(1, 19) = 3.32$, $p < .08$; and the VS task produced significantly longer latencies, $F(1, 19) = 19.74$, $p < .001$. Thus, the three distraction tasks constitute three increasing levels of interference: from FS to FL to VS. There was also a significant main effect for Presentation Condition, $F(1, 19) = 12.42$, $p < .01$, indicating that within-field matches (584.19 ms) were performed more quickly than across-field matches (605.57 ms).

Of most consequence, the ANOVA revealed a significant Task × Presentation Condition interaction, $F(4, 76) = 3.06$, $p < .05$. As in Experiment 1, to interpret this interaction, we subtracted within-field reaction time from across-field reaction time to obtain
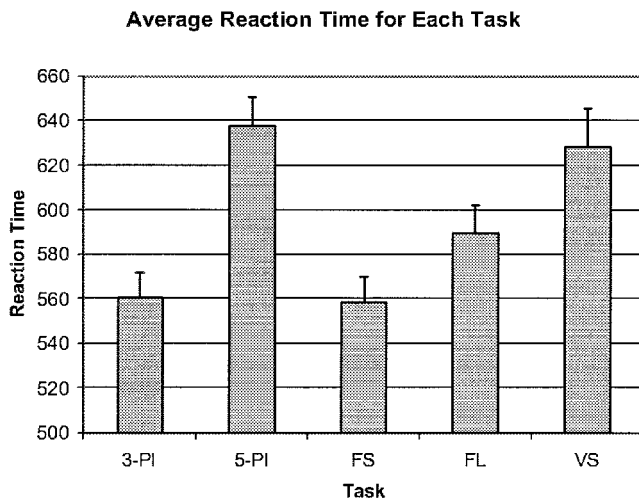
Average Reaction Time for Each Task

Figure 5. Overall reaction time for each task ($+SE$). PI = physical identity; FS = fixed symbol; FL = fixed letter; VS = variable symbol.

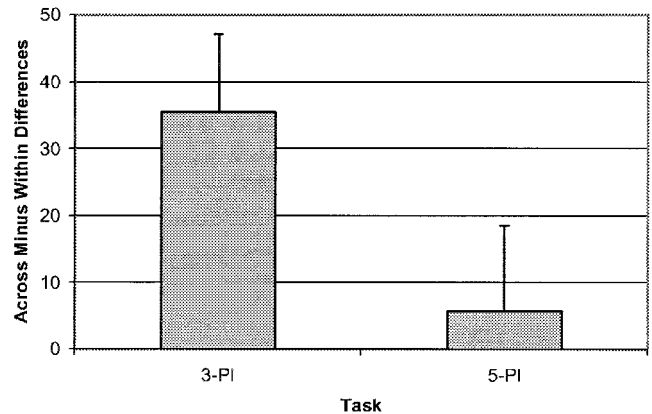### Across-Hemisphere Minus Within-Hemisphere RT Differences for Each Task

Figure 6. Reaction time (RT) scores for the 3-physical identity (PI) and 5-PI tasks ($+SE$).

difference scores that reflect the hemispheric processing advantage. Positive differences indicate a unilateral advantage, and negative differences indicate a bihemispheric advantage. As shown in Figure 6, increasing the number of relevant targets in the five-PI compared with the three-PI task reduces the within-hemisphere advantage, $F(1, 19) = 4.47$, $p < .05$. Thus, there is a significant shift toward bihemispheric processing for the five-PI task compared with the three-PI task as we expected based on previous results (e.g., Belger & Banich, 1992; Reuter-Lorenz et al., 1999). For the distraction conditions, the progressive increase in distraction from FS to FL to VS is associated with stepwise increments in the within-hemisphere advantage, as shown in Figure 7. Tests of simple effects indicate that although the unilateral processing advantages for the FS and FL do not differ from each other, $F(1, 19) = 0.89$, $p > .3$, the unilateral advantage for the VS task is significantly different from that of the FS task, $F(1, 19) = 7.51$, $p < .01$, and differs marginally from the FL condition, $F(1, 19) = 3.23$, $p < .08$. Finally, the unilateral advantage in the VS condition differs significantly from that of the five-PI task, $F(1, 19) = 7.03$, $p < .01$, but not from that of the three-PI task, $F(1, 19) = 0.29$, $p > .5$. Thus, in the VS condition where distractors have the greatest effect, there is also the strongest unilateral processing advantage compared with the other distractor tasks and to the five-PI task. The reaction times appear in Table 3.

Accuracy

The accuracy results parallel the reaction time results. Unlike the three-PI task, the five-PI task is associated with a bilateral

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[4] As in Experiment 1, the accuracy on no-go trials cannot provide information about within- or across-field advantages and were, therefore, analyzed separately. False alarms were most frequent in the five-PI condition (11.6%), corroborating the other accuracy and reaction time measures indicating that this was the most difficult condition. The five-PI false alarm rate differed significantly from the other conditions, for which the false alarm rates were statistically equivalent, three-PI (4.1%), FL (3.8%), FS (4.3%), and VS (4.1%); $F(4, 76) = 12.35$, $p < .001$.

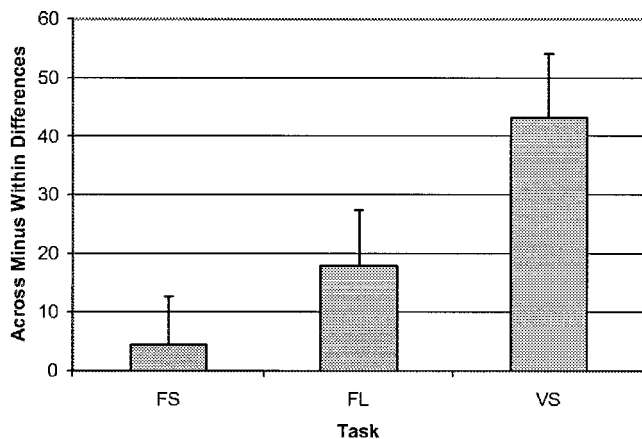## Across-Hemisphere Minus Within-Hemisphere RT Differences for Each Task

Figure 7. Reaction time (RT) scores for the fixed symbol (FS), fixed letter (FL), and variable symbol (VS) tasks ($+SE$).

processing advantage. In contrast, the inclusion of distractors leads to a unilateral advantage especially when the filtering demands are high. An ANOVA revealed a main effect for Task, $F(4, 76) = 6.94$, $p < .001$. Contrasts indicate that accuracy is significantly lower in the five-PI task compared with each of the other tasks (all $ps < .01$), which do not differ from each other (mean percentage correct is presented in Table 4). There was also a significant Task × Condition interaction, $F(4, 76) = 4.23$, $p < .01$. Unlike the three-PI, the five-PI task produced a marginal across-hemisphere advantage, $F(1, 19) = 3.63$, $p = .06$, again replicating previous results (Belger & Banich, 1992; Reuter-Lorenz et al., 1999). In contrast, the FL and VS distractor conditions produced a within-hemisphere advantage, $F(1, 19) = 7.78$, $p < .01$, and $F(1, 19) = 8.14$, $p < .01$, respectively.

Difference scores can again be used to illustrate these effects. The within-field accuracy was subtracted from across-field accuracy to obtain difference scores indicative of the hemispheric processing advantage. Positive differences indicate an across-hemisphere or bihemispheric advantage, and negative differences indicate a within-hemisphere or unilateral advantage. Contrasts reveal unilateral processing advantages in both the FL and VS tasks, which differ significantly from the FS task, $F(1,$

$19) = 4.21$, $p < .05$, and $F(1, 19) = 4.40$, $p < .05$, respectively. Furthermore, the unilateral processing advantages of the FL and VS tasks differ significantly from the bihemispheric processing advantage of the five-PI task, $F(1, 19) = 11.03$, $p < .005$, and $F(1, 19) = 11.32$, $p < .005$, respectively.

By manipulating the level of visual distraction, we successfully influenced the effects of presentation condition. The need for greater filtering, as evident in the performance decline across distraction conditions, increased the within-field advantage. Put another way, interhemispheric interactions were more detrimental to performance as the need for filtering increased. These results support the proposal that modulating interhemispheric interactions can insulate lateralized processing operations.

General Discussion

Our investigation provides new evidence that callosally mediated interhemispheric interactions contribute to attention. Although we have no direct measures of interhemispheric interactions, our conclusions rest on the reasonable assumption that such interactions are more prevalent for across-field matches than for within-field matches. By manipulating the attentional requirements and comparing performance on within-field with across-field match conditions, we measured the relative performance cost or benefit of requiring such interactions. Accordingly, each experiment advances our understanding of attentional contributions of the corpus callosum with evidence that it mediates two major functions: resource allocation and selective filtering.

Experiment 1 demonstrates constraints on the kinds of resource demands that promote a bihemispheric processing advantage. Concurrent tone counting and letter matching produced mutual interference at some processing stages, as was evident by the performance decline in the DT compared with the single task conditions. However, the absence of a shift toward a bihemispheric advantage in the presence of this increased demand suggests specificity in the resource allocation functions of callosally mediated interactions. As the three-NI task results reveal, when the load on letter processing operations increases, there is a shift toward bilaterality. We interpret the lack of this shift in the DT condition to mean that the increased resource demand or load imposed by tone counting did not draw on the specific resources recruited by letter processing operations; moreover, such specificity is required to promote a performance advantage under bilateral presentation conditions.

The results from this experiment also bear on an earlier result reported from our lab involving the effects of normal aging on

Table 3

Average Reaction Time and Standard Error Scores in Each Letter Matching Task Under Within-Hemisphere and Across-Hemisphere Conditions, and the Across Minus Within Difference for Each Task

Task	Three-PI task		Five-PI task		FS		FL		VS	
	M	SE	M	SE	M	SE	M	SE	M	SE
Within	542.92	14.94	634.57	19.00	555.99	17.23	580.57	17.40	606.88	23.64
Across	578.50	16.19	640.35	18.49	560.53	16.02	598.42	19.28	650.04	24.24
Combined	560.71	11.13	637.46	13.17	558.28	11.7	589.49	12.94	628.46	16.99
Across − Within	35.58		5.78		4.54		17.85		43.16	

Note. PI = physical identity; FS = fixed symbol; FL = fixed letter; VS = variable symbol.

Table 4
Average Accuracy and Standard Error Scores in Each Letter Matching Task Under Within-Hemisphere and Across-Hemisphere Conditions, and the Across Minus Within Difference for Each Task

Task	Three-PI task		Five-PI task		FS		FL		VS	
	M	SE	M	SE	M	SE	M	SE	M	SE
Within	93.2	2.7	82.6	2.4	94.5	1.7	94.0	2.4	93.2	1.7
Across	93.2	2.5	85.0	2.6	94.6	1.5	90.5	2.6	89.6	2.1
Combined	93.2	1.8	83.8	1.8	94.6	1.1	92.2	1.7	91.4	1.4
Across − Within	0		2.4		0.1		−3.5		−3.6	

Note. PI = physical identity; FS = fixed symbol; FL = fixed letter; VS = variable symbol.

bihemispheric processing. In an experiment that tested performance on three-PI, five-PI, and five-NI tasks, we found that compared with younger adults, older adults generally performed better in the across-field than within-field match conditions, showing a bihemispheric processing advantage at lower levels of task complexity than did younger adults (Reuter-Lorenz et al., 1999). This outcome provides evidence that recruiting resources from both hemispheres is particularly advantageous as we age. The results from Experiment 1 in this article suggest that the superior bihemispheric processing of older adults reflects the recruitment of bilateral task-specific resources rather than compensation for generalized resource declines. Bihemispheric processing may permit parallel task-specific computations (e.g., concurrent processing of letter identities) and not simply general resource recruitment (e.g., increased neural circuits or computational space). According to Experiment 1, the principles governing bihemispheric recruitment may be better described by theories of task-specific resource pools (Wickens & Liu, 1988) than those that propose undifferentiated resource pools (Kahneman, 1973).

Experiment 2 demonstrates that under some conditions, visual selection can operate more efficiently when processing can be restricted to information presented within a single visual field rather than distributed across the two hemifields. Our results corroborate previous studies indicating that the need to filter irrelevant stimuli has a cost on performance. We also showed that this cost is greater when the irrelevant stimuli are visually similar to the target items and when their location is uncertain. An important new result is that the cost of filtering can be reduced when interhemispheric interactions are minimized. One way to think about this result is to assume that by lateralizing the stimulus presentation, each hemisphere can function as a separate input channel (Broadbent, 1958). By minimizing the cross talk between these channels (by presenting the matching items within the same visual field) distractors in one hemisphere can be filtered from processing in the other hemisphere. However, if the probe and matching target are presented to opposite channels, then interhemispheric cross talk is essential, the overall level of distraction is increased, and performance is reduced on across-field compared with within-field trials. According to this proposal, early visual filtering is accomplished in part by minimizing interhemispheric interactions. The resource recruitment function of the corpus callosum was evident in the shift toward bilateral processing in the five-PI task in which every item is relevant. In stark contrast, the

five-item distractor tasks, in which two items are always irrelevant, increased the within-hemisphere advantage. This latter finding supports the hypothesis that interhemispheric interactions serve as a selective gating mechanism. Thus, the data from these two experiments suggest that interhemispheric interactions serve two distinct functional roles in attentional control.

Note, however, that Weissman and Banich (1999) reported a result that seems to conflict with our own. Their manipulations were intended to increase attentional selectivity and led to an increased bilateral processing advantage (see also Liederman, 1998). The difference between their results and our own can be explained if we consider the computational complexity of their matching task and the filtering requirements. In the global–local paradigm used by Weissman and Banich (1999), hierarchical stimuli were presented to both hemispheres, and match decisions were made based on the identity of the forms appearing at a prespecified global or local level. They found that across-hemisphere presentations were advantageous when the information at the unattended level conflicted with the attended level (incompatible condition). They proposed that the incompatible hierarchical stimuli increase the computational complexity of the task compared with compatible stimuli because the former require both perceptual and response selection, whereas the latter do not. Note that this increased complexity is due in part to the fact that the relevant and irrelevant dimensions were integral attributes of the same visual configuration. Accordingly, in the incompatible condition and in contrast to our Experiment 2, selection could not simply be based on the hemispheric input channel. Moreover, the unattended level contained task relevant information, because it could be associated with a response, thereby necessitating selection during decision and responses stages as well. In contrast, the irrelevant distractors in our experiment did not introduce response competition and could be filtered on the basis of alphanumeric category or spatial position. Because both attributes can be coded and filtered early in the processing stream (Pashler, 1998), the computational demands imposed by these irrelevant items are minimized.

Experiments 1 and 2 provide new insights into the relation between task difficulty and the advantage from bihemispheric processing. Our results demonstrate that it is incorrect to claim that bihemispheric processing is universally enhanced to meet increases in task difficulty. Indeed, we demonstrated that changes in hemispheric processing crucially depend on how difficulty is manipulated. Using change in overall reaction time as a crude, but

legitimate, index of task difficulty, we see the following patterns: Difficulty variations due to computational complexity increase the bihemispheric processing advantage, difficulty variations due to the demand for selective filtering decrease the bihemispheric processing advantage, and difficulty variations due to a general increase in processing demand do not alter the processing advantage.

The distinction between processing demand and task difficulty is important for interpreting the effects of the DT condition in Experiment 1. One may argue that the absence of a hemispheric processing alteration in this condition was because the DT was not difficult enough. Two features of our data set counter this interpretation. First, using the same criteria used to compare other conditions overall reaction time was significantly longer in the DT condition than in the three-PI condition, indicating a significant increase in difficulty. Second, comparable changes in overall reaction time, in the fixed letter versus variable symbol conditions, for example, were associated with alterations in the hemispheric processing advantage. Together these observations argue that the advantage from bihemispheric processing is determined by the nature of the task demand that is varied rather than mere variations in difficulty.[5]

We offer an important and useful caveat about our approach. Resource recruitment and selective processing are likely to be required at different stages and to varying degrees by most tasks. Our attentional manipulations were intended to vary selectively one dimension of attentional control or the other. Yet, we acknowledge that any given manipulation is unlikely to affect purely one and only one attentional dimension. Nonetheless, we believe we were successful in producing sufficiently selective effects in each experiment to warrant an interpretation in terms of resource allocation to meet computational demands in Experiment 1 and attentional filtering of distractors in Experiment 2.

An important direction for future research is to examine the changing roles of interhemispheric interactions across the life span, especially in the domain of attentional control. Developmental changes in young children suggest that selective insulation between the hemispheres develops between 10 to 14 years of age (Liederman, Merola, & Hoffman, 1986; Merola & Liederman, 1985). In contrast, increased age (from 6.5 to 14 years of age) has been associated with decreases in bihemispheric advantages at high levels of computational complexity (Banich, Passarotti, & Janes, 2000). Such developmental changes can be linked to faster interhemispheric transfer (Hagelthorn, Brown, Amano, & Asarnow, 2000). At the other end of the life span, older adults (65 to 75 years of age) demonstrate a bihemispheric advantage at lower levels of task complexity compared with their younger counterparts (18 to 25 years of age), but they experience impaired sensorimotor transfer (Reuter-Lorenz & Stanczak, 2000). Thus, there appear to be differential changes in interhemispheric interactions across the life span, and the tasks presented in this article could be used to characterize the development of attentional functions.

Future work could further examine the role of hemispheric specialization in the attentional functions of interhemispheric interactions. For instance, using DT methods, concurrent tasks could be selected such that they depend more strongly on one hemisphere than the other (Grimshaw, 1998; Hellige & Cowin, 1996; Hellige & Cox, 1976). Additionally, variations in DT demands could be combined with variations in computational complexity to examine trade-offs between the filtering and resource allocation

functions of interhemispheric interactions. These approaches could further clarify the specificity of resource demands that promote a bihemispheric advantage in addition to the selection demands that promote a unilateral advantage.

In sum, our results provide further evidence that interhemispheric interactions play at least two specific roles in the cortical control of attentional processes. Interhemispheric interactions are advantageous when lateralized processors can be jointly recruited to perform parallel, task-specific computations, thereby increasing the availability of task-specific resources. Contrarily, when there is a need for early sensory filtering, lateralized processing can be particularly advantageous, suggesting that the corpus callosum can selectively filter irrelevant input from the opposite hemisphere.

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[5] Interestingly, the three-PI task is presumably more demanding in Experiment 2 (M reaction time $= 560.71$ ms) than in Experiment 1 (M reaction time $= 495.44$ ms); however, this differential amount of difficulty was met with a stronger unilateral advantage (within-hemisphere processing advantage for the three-PI task in Experiment 2 $= 35.58$, and in Experiment 1 $= 9.33$). This difference could reflect the context in which the three-PI task is performed, in that with more difficult tasks, the ease of the three-PI task might be exacerbated. Nonetheless, this result further demonstrates that overall task difficulty does not simply or necessarily result in a bihemispheric advantage.

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We provide this form to assist members, institutions, and nonmember individuals with any subscription problems. With the appropriate information we can begin a resolution. If you use the services of an agent, please do **NOT** duplicate claims through them and directly to us. **PLEASE PRINT CLEARLY AND IN INK IF POSSIBLE.**

_____
PRINT FULL NAME OR KEY NAME OF INSTITUTION

_____
ADDRESS

_____
CITY   STATE/COUNTRY   ZIP

_____
YOUR NAME AND PHONE NUMBER

TITLE

_____
MEMBER OR CUSTOMER NUMBER (MAY BE FOUND ON ANY PAST ISSUE LABEL)

_____
DATE YOUR ORDER WAS MAILED (OR PHONED)

____PREPAID ____CHECK ____CHARGE
          CHECK/CARD CLEARED DATE:_____

(If possible, send a copy, front and back, of your cancelled check to help us in our research of your claim.)

          ISSUES: ____ MISSING ____ DAMAGED

VOLUME OR YEAR   **NUMBER OR MONTH**

TITLE	VOLUME OR YEAR	NUMBER OR MONTH
_____	_____	_____
_____	_____	_____
_____	_____	_____

Thank you. Once a claim is received and resolved, delivery of replacement issues routinely takes 4–6 weeks.

━━━━ **(TO BE FILLED OUT BY APA STAFF)** ━━━━

DATE RECEIVED: _____   DATE OF ACTION: _____
ACTION TAKEN: _____   INV. NO. & DATE: _____
STAFF NAME: _____   LABEL NO. & DATE: _____

Send this form to APA Subscription Claims, 750 First Street, NE, Washington, DC 20002-4242

PLEASE DO NOT REMOVE. A PHOTOCOPY MAY BE USED.