

An unbalanced distribution of inputs across the hemispheres facilitates interhemispheric interaction

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Abstract

In this study, we investigated 2 possible mechanisms by which interhemispheric interaction (IHI) might facilitate performance. Twenty university students performed 3- and 4-item versions of a less complex physical identity (PI) task in which they decided whether 2 letters were perceptually identical (e.g., 'A' and 'A') and a more complex name identity (NI) task in which they decided whether 2 letters had the same name (e.g., 'A' and 'a'). Consistent with prior work, IHI facilitated performance more for the relatively complex NI task than for the simpler PI task regardless of how many items were in the display. However, for each task IHI facilitated performance less in the 4-item displays than in the 3-item displays. These results indicate that IHI facilitates performance by allowing (1) a division of processing across the hemispheres, and (2) task-relevant information to be processed by a hemisphere that receives a relatively light processing load. (*JINS*, 2000, 6, 313–321.)

Keywords: Interhemispheric interaction; Laterality, Letter matching, Task complexity

INTRODUCTION

Numerous studies have demonstrated that the cerebral hemispheres process information in different ways (e.g., Sperry, 1974), but only recently have investigators begun to explore how the hemispheres coordinate their processing and the effect that such coordination has on task performance (e.g., Banich & Belger, 1990; Liederman, 1986, 1998). Since each hemisphere is a somewhat independent processor (Friedman & Polson, 1981), coordinating processing across the hemispheres might be advantageous in certain situations. A hemispheric division of processing would likely permit more computational power to be brought to bear upon task performance than would be possible if a task were directed to a single hemisphere because it would allow more brain regions to be recruited for task performance (Banich & Belger, 1990). This increase in computational power might be especially beneficial for complex tasks that require relatively large numbers of computations to be performed (e.g., Banich & Belger, 1990; Belger & Banich, 1992).

Consistent with this view, a number of investigators have reported that interhemispheric interaction (IHI) facilitates performance, especially for attentionally demanding or computationally complex tasks (Banich, 1998; Banich & Belger, 1990; Banich & Passarotti, 1999a; Belger & Banich, 1992, 1998; Brown & Jeeves, 1993; Copeland & Zaidel, 1996; Dimond & Beaumont, 1972; Hellige, 1987; Sereno & Kosslyn, 1991; Weissman & Banich, 1999). The robustness of this effect is underlined by the wide range of complex tasks performed more quickly and/or more accurately when the two items critical for reaching a decision are directed to different hemispheres (across-hemisphere trials, which require IHI) rather than to the same hemisphere (within-hemisphere trials, which do not require IHI). For example, determining that one digit's value is less than another's (Banich & Belger, 1990, Experiment 3), deciding that two letters have the same name (e.g., 'A' and 'a') (Banich & Belger, 1990, Experiment 1), responding that two geometric forms have the same shape even though they differ in color (Banich & Passarotti, 1999a), and determining that two hierarchical stimuli are identical at a prespecified level (e.g., local) even though they differ at the irrelevant level (e.g., global; Weissman & Banich, in press a) are all performed better when the two critical items are directed to different hemispheres, rather than to the same one. In contrast, the degree to which IHI facilitates performance is re-

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duced for less complex tasks such as determining whether two items are perceptually identical (e.g., Banich & Belger, 1990; Banich & Passarotti, 1999a) or deciding that two hierarchical stimuli are identical at a prespecified level (e.g., local) when they are also identical at the irrelevant level (e.g., global; Weissman & Banich, 1999). Of importance, there is evidence that comparing two items (e.g., letters) in terms of their semantic identity is more complex than determining whether two items are perceptually identical (e.g., Posner & Mitchell, 1967). Further, there is abundant evidence from experiments using event-related potential (e.g., Coles et al., 1985), functional neuroimaging (e.g., Bush et al., 1998; Pardo et al., 1990) and negative priming paradigms (e.g., Neill, 1977; Tipper, 1985; Tipper & Cranston, 1985; see Tipper & Milliken, 1996, for a discussion) indicating that additional processes are evoked in selective attention paradigms when incompatible distracters are present relative to when they are not. Hence, the existing data are quite consistent with our view that IHI facilitates the performance of complex tasks more than it facilitates the performance of simpler tasks.

Banich and colleagues have proposed that the degree to which IHI facilitates performance is determined jointly by two factors: (1) the number of computational steps required to perform a task; and (2) the costs of integrating information across the hemispheres (Banich & Belger, 1990; Belger & Banich, 1992; see Banich, 1995, for a discussion). Their model assumes that even though the hemispheres have distinct specializations, for most tasks each hemisphere can make a contribution. When computational complexity is relatively low, the advantages of dividing operations across the hemispheres (e.g., greater computational power) are insufficient to outweigh the costs of integrating information across the corpus callosum (e.g., time costs, stimulus degradation), leading to a within-hemisphere advantage. However, as task complexity increases the benefits of dividing processing across the hemispheres become larger relative to the costs. This situation may result in a smaller within-hemisphere advantage (relative to a condition that produces a large within-hemisphere advantage) or in a larger across-hemisphere advantage (relative to a condition that produces a small across-hemisphere advantage). In both of these cases, the benefits of IHI become larger relative to the costs and, therefore, we say that across-hemisphere processing becomes more advantageous to performance as task complexity increases. Analogously, if the costs of IHI become larger relative to the benefits, the result may be either a smaller across-hemisphere advantage (relative to a condition that produces a large across-hemisphere advantage) or a larger within-hemisphere advantage (relative to a condition that produces a small within-hemisphere advantage). In these cases, the costs of IHI become larger relative to the benefits and, hence, we say that across-hemisphere processing becomes less advantageous to performance as task complexity decreases. The only exception to the patterns above occurs when only one hemisphere is capable of performing a specific operation (e.g., phonetic processing; see Belger &

Banich, 1998), in which case IHI does not become more advantageous to performance as task complexity increases.

In the present study, we investigated whether a third factor should be added to Banich and colleagues' model. Specifically, we investigated whether the degree to which IHI facilitates performance also depends upon whether the hemispheres receive equal as compared to unequal numbers of inputs. In many of the studies conducted by Banich and colleagues, a three-item paradigm is employed (see Figure 1) in which unequal numbers of inputs are directed to the right and left hemispheres [e.g., one item to the right hemisphere (RH) and two items to the left hemisphere (LH)].

Evidence from these prior studies suggests that this unequal processing load may influence performance. For example, the unequal processing load appears to influence which hemisphere makes the match decision on across-hemisphere trials. Notice that on both across LVF and across RVF trials (refer back to Figure 1) either hemisphere is capable of making the match decision since each hemisphere receives one of the matching letters. It has been found that the hemisphere making the match decision is the one that receives the lighter perceptual processing load (see Banich, 1995, and Banich & Belger, 1990, for a discussion of this idea). Thus, the left hemisphere makes the match decision on across LVF trials, whereas the right hemisphere makes the match decision on across RVF trials. Support for this viewpoint comes from a study in which one group of individuals was induced into a neutral mood state and another

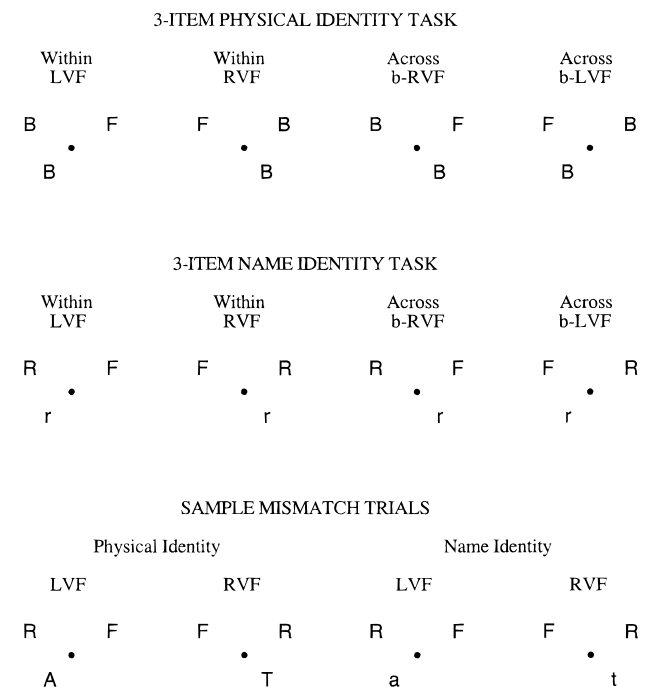


Fig. 1. Sample trials for the three-item versions of the PI and NI tasks in the present study. Across-hemisphere processing may be especially advantageous to performance in three-item paradigms because it allows one of the critical items to be directed to a relatively unburdened hemisphere that receives only one input.

was induced into a sad mood state (Banich et al., 1992). Consistent with other studies in which a sad mood state has a more deleterious effect on right- than left-hemisphere performance (e.g., Ladavas et al., 1984), induction into a sad mood state elongated reaction time more for within-LVF trials than for within-RVF trials. Likewise, a sad mood state elongated reaction time more for across-RVF trials than for across-LVF trials, suggesting that the match decision is made by the right hemisphere for the former, but by the left hemisphere for the latter. Hence, in three-item paradigms the match decision on across-hemisphere trials is made by the hemisphere that receives the lighter perceptual processing load (i.e., by the hemisphere that receives just one item). Therefore, one way that IHI appears to facilitate performance is by allowing for a distribution of the processing load across the hemispheres (i.e., the majority of perceptual processing is performed by one hemisphere while the majority of the decision process is performed by the other hemisphere).

In the present study, we consider whether the unequal processing load in the three-item paradigm might influence the overall degree to which IHI aids performance, not just which hemisphere makes the match decision on across-hemisphere trials. In particular, we consider whether IHI might be especially advantageous to performance in three-item paradigms because on across-hemisphere trials one of the critical items is processed by a relatively unburdened hemisphere that receives only one item. In contrast, on within-hemisphere trials both of the critical items are directed to a more burdened hemisphere that receives two inputs. When one of the critical items is the only item presented to a hemisphere, as occurs on across-hemisphere trials, it could be processed more efficiently than when it is presented to a hemisphere that also receives a second item, as occurs on within-hemisphere trials. Thus, in three-item paradigms IHI might facilitate performance not only because it allows a task to be divided across two hemispheres rather than one, but also because it allows one of the critical items to be processed by a relatively unburdened hemisphere.

Contrast the three-item paradigm with a four-item paradigm in which equal numbers of items (i.e., two) are directed to each hemisphere. As can be seen in Figure 2, each critical item is directed to a hemisphere that receives two task-relevant inputs—not only on within-hemisphere trials, but also on across-hemisphere trials.¹ In such a four-item paradigm, performance on across-hemisphere trials cannot be facilitated because one of the critical items is directed to a relatively unburdened hemisphere because each hemisphere always receives two task-relevant inputs. Thus, we predicted that IHI should be less advantageous to perfor-

¹Although previous investigators have employed four-item paradigms (e.g., Copeland & Zaidel, 1996; Nicholas & Marsolek, 1997; Yoshizaki & Tsuji, 1999), in these paradigms not all four of the items were task-relevant (i.e., some items were distracters). Thus, directing the critical items to different hemispheres as compared to the same one may still have facilitated performance by allowing critical information to be processed by a hemisphere with a relatively light processing load.

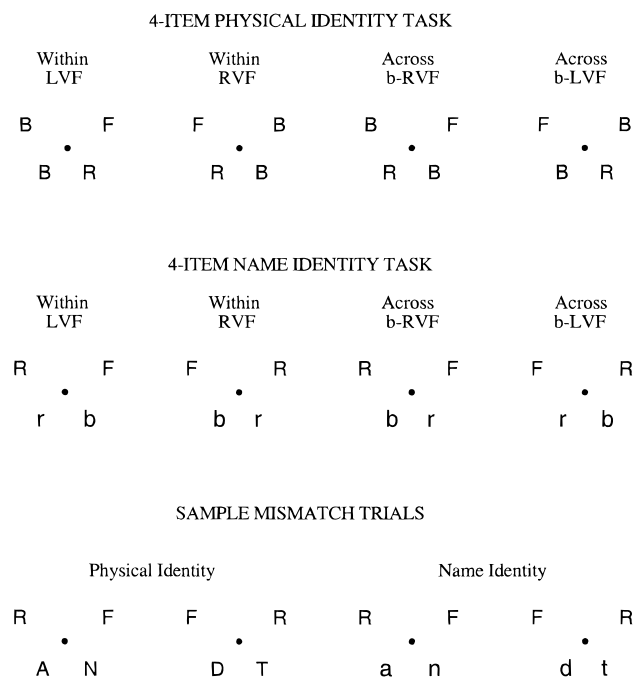


Fig. 2. Sample trials for the four-item versions of the PI and NI tasks in the present study. Across-hemisphere processing may be less advantageous to performance in a four-item paradigm than in a three-item paradigm because the four-item paradigm does not allow one of the critical items to be processed by a relatively unburdened hemisphere that receives only one input.

mance when the hemispheres receive equal numbers of inputs (i.e., in four-item paradigms) than when they receive unequal numbers of inputs (e.g., in three-item paradigms) (see Copeland, 1996, for similar ideas).

To test our hypothesis, we investigated whether the degree to which IHI facilitates the performance of two letter matching tasks is reduced when the hemispheres receive equal as compared to unequal numbers of inputs. In a less complex physical identity (PI) task, participants were asked to decide whether any target item beneath fixation was perceptually identical (e.g., 'B' and 'B') to a probe item above fixation (see Figures 1 and 2). In a more complex name identity (NI) task, participants were asked to decide whether any target beneath fixation had the same name (e.g., 'a' and 'A') as a probe item above fixation (see Figures 1 and 2). Note that the NI task is more complex than the PI task because each item in the display requires not only perceptual processing but also that its categorical identity be accessed (e.g., Posner & Mitchell, 1967).

The PI and NI tasks are especially well-suited for investigating how IHI modulates performance because data from split-brain patients indicates that each of these tasks can be performed by the right and left cerebral hemispheres of the brain (Eviatar & Zaidel, 1994). Converging evidence from neurologically intact individuals indicates that the RH may perform the NI task by generating a visual representation of the opposite-case version of one of the matching letters in the display rather than by accessing the phonological rep-

representations of the letters (Boles, 1992; Boles & Eveland, 1983). Thus, it is reasonable to suppose that both the PI and the NI task can be performed either by a single hemisphere working relatively independently or by both hemispheres working together.

To investigate how IHI modulates the performance of the PI and NI tasks, we compared performance on within-hemisphere match trials, which do not require IHI to reach a decision, to performance on across-hemisphere trials, which do require IHI to reach a decision. To examine whether equating the number of inputs to each visual field reduces the degree to which IHI facilitates performance for each task, we compared performance in three-item displays (Figure 1), in which the hemispheres receive unequal numbers of inputs, to performance in four-item displays (Figure 2), in which the hemispheres receive equal numbers of inputs. In the three-item version of each task (i.e., the paradigm used by Banich & Belger, 1990, and Belger & Banich, 1992, 1998), participants decided if the single target item beneath fixation matched either of the two probes above fixation. In the four-item version of each task, they determined whether either bottom target item matched either top probe item. Of importance, the four-item displays equate the perceptual and cognitive loads imposed on each hemisphere while the three-item displays do not.

We made two predictions. First, consistent with prior studies (e.g., Banich & Belger, 1990) we predicted that IHI would facilitate performance more for the relatively complex NI task than for the simpler PI task. Second, we predicted that IHI would facilitate the performance of each task less in the four-item displays than in the three-item displays because, in the four-item displays, the hemispheres are equally burdened and therefore across-hemisphere processing can no longer facilitate performance by allowing one of the critical items to be directed to a less burdened hemisphere.

METHODS

Research Participants

Twenty-three right-handed University of Illinois students (12 male, 11 female) with normal or corrected-to-normal vision were paid \$10 for participating in the experiment.

Stimuli

The stimuli were 9 capital letters ('A,' 'B,' 'F,' 'G,' 'H,' 'N,' 'D,' 'R,' 'T') and their lowercase counterparts. The capital letters were displayed in Geneva 38-point bold font. The lowercase letters were displayed in Geneva 44-point bold font to make them more equivalent to the capital letters in terms of size and discriminability. All stimuli subtended a maximum of 1.0° of visual angle horizontally and vertically. In each four-item trial, four stimuli were presented. Two target letters were centered 2.0° beneath fixation, one 2.0° to the left and the other 2.0° to the right. Two probe

letters were centered 2.0° above fixation, one 4.0° to the left and the second 4.0° to the right. All stimuli were displayed as black letters on a white background. The three-item trials were identical to the four-item trials except that only one bottom target item appeared. A Macintosh Centris 650 equipped with a 39-cm color monitor and SuperLab software was used to present the stimuli and to collect participants' responses.

Procedure

After being screened for possible visual problems and for handedness, each participant performed two tasks. In the physical identity (PI) task, participants decided if a target letter beneath fixation was perceptually identical to one of the two probes above fixation (e.g., 'A' and 'A'). In the name identity (NI) task, participants decided if a target beneath fixation had the same name as one of the probes (e.g., 'A' and 'a'). The trials for these two tasks were blocked and their order was counterbalanced across participants. There were 96 practice trials and four blocks of 144 test trials for each task. To maintain a high level of performance, feedback was provided to participants in the form of a short auditory tone that was played whenever an error was made.²

The performance of each task was measured in both three-item and four-item displays for each participant. On each trial of both tasks, participants viewed a fixation dot for 500 ms and then saw the stimulus array for 200 ms. Participants responded via a keypress using the middle and index fingers to indicate either a match or a mismatch decision (response-key decision mappings were counterbalanced across participants). In the three-item displays, participants used one finger (e.g., middle finger) to press one computer key (e.g., the 'G' key) if the bottom target matched either probe (50% of trials) and another finger (e.g., index finger) from the same hand to press another key (e.g., the 'H' key) if the target matched neither probe (50% of trials). In the four-item displays, participants were asked to decide whether either bottom target matched either probe. The three- and four-item trials occurred in different trial blocks that were nested within each of the two tasks. The order of the three- and four-item conditions within each task was counterbalanced across participants.

On within-hemisphere match trials, no IHI was required since both matching items appeared in the same visual field, either in the left visual field (within-LVF trials) or in the right visual field (within-RVF trials). On across-hemisphere match trials, IHI was required since the matching items appeared in different visual fields, either with the target in the RVF and probe in the LVF (across-b-RVF trials) or with the target in the LVF and probe in the RVF (across-b-LVF tri-

²In an unpublished study, we found that the error rate for the four-item NI task was relatively high (approximately 25%) when no feedback was provided. Since reaction time is not as easily interpreted when error rates are high, in the present study we provided feedback on each trial to encourage participants to perform accurately.

als). The different trial types—within-LVF, within-RVF, across-b-RVF, and across-b-LVF—appeared equally often in match trials (no distinction between within and across trial types was possible in mismatch trials; refer back to Figures 1 and 2).

Finally, we counterbalanced two additional variables. First, to preclude a response bias from developing on the basis of an item's position in the display, each stimulus appeared in each possible location an equal number of times on match and mismatch trials. Second, to ensure that our hemispheric and interhemispheric effects could not be driven by a unilateral response mode, each participant performed half of the three- and four-item trials for each task with the right hand and half with the left hand. Left and right hand trials were performed in different trial blocks that were nested within the three- and four-item trials for each task. The order of left- and right-hand blocks was counterbalanced across participants.

RESULTS

Three participants whose error rates for the four-item NI task exceeded 30% were excluded from the analysis (although the data are quite similar whether or not they are included). Thus, only the data from the remaining 20 participants (10 male, 10 female) were analyzed. These data were entered into separate repeated-measures analyses of variance for average reaction times for correct match trials and average error rates for match trials with the following within-participants factors: number of items (three or four), task (PI, NI), response hand (right, left), and trial type (within-LVF, within-RVF, across-b-RVF, across-b-LVF). All trials in which an incorrect response was made or in which reaction time exceeded 3000 ms were counted as errors. All reaction times were measured from stimulus offset to response. The main findings are summarized in Table 1.

Reaction Time (RT)

As expected, there was a significant main effect of number of items because responses were significantly faster for the

three-item displays (522 ms) than for the four-item displays [725 ms; $F(1, 15) = 132.452, p < .0001$]. Also, as predicted, there was a significant main effect of task [$F(1, 23) = 254, p < .0001$] because RT was faster for the less demanding PI task (498 ms) than for the more demanding NI task (748 ms). There was also a significant interaction between Number of Items \times Task [$F(1, 15) = 41.282, p < .0001$] because the increase in RT produced by employing a four-item as compared to a three-item display was larger for the more complex NI task [278 ms; $F(1, 19) = 124.57, p < .001$], than for the less complex PI task [129 ms; $F(1, 19) = 60.051, p < .001$].

There was also a significant main effect of trial type [$F(1, 19) = 5.709, p < .002$], which was qualified by several interactions. Of most importance to the present study, there was a significant interaction between Number of Items \times Trial Type [$F(3, 57) = 8.490, p < .0002$]. As predicted, a planned contrast revealed that across-hemisphere processing was significantly less advantageous to performance for the four-item displays (72-ms within-hemisphere advantage) than for the three-item displays [23-ms across-hemisphere advantage; $F(1, 19) = 48.867, p < .0001$]. Replicating prior studies (e.g., Banich & Belger, 1990), there was also a significant interaction between Task \times Trial Type [$F(3, 57) = 49.825, p < .0001$]. As expected, a planned contrast revealed that across-hemisphere processing was significantly more advantageous to performance for the NI task (48-ms across-hemisphere advantage) than for the PI task [101-ms within-hemisphere advantage; $F(1, 19) = 161.074, p < .0001$].

Finally, there was a significant interaction between Number of Items \times Task \times Trial Type [$F(3, 57) = 15.151, p < .0001$], because the degree to which IHI facilitated performance was reduced on four-item trials relative to three-item trials, but only for the PI task. Indeed, for the PI task across-hemisphere processing was significantly less advantageous to performance on four-item trials than on three-item trials [$F(1, 19) = 107.595, p < .0001$], because the 18-ms within-hemisphere advantage on three-item trials [$F(1, 19) = 4.081, p < .058$] became a 184-ms within-hemisphere advantage on four-item trials [$F(1, 19) = 140.560, p < .0001$]. In contrast, for the NI task, the across-hemisphere advantage on four-item trials [41 ms; $F(1, 19) = 7.761, p < .02$] was not significantly smaller than the across-hemisphere advantage on three-item trials [55 ms; $F(1, 19) = 43.112, p < .0001; F(1, 19) < 1$].

Although the absolute size of the across-hemisphere advantage for the NI task was not significantly smaller on four-item trials than on three-item trials, RT for the NI task was 278 ms longer on four-item trials than on three-item trials. Since baseline RT differed so greatly for the four-item and three-item NI tasks, we decided to test whether the across-hemisphere advantage for the NI task expressed as a percentage of mean RT was smaller on four-item trials than on three-item trials. To do so, we computed the across-hemisphere advantage expressed as a percentage of mean RT in each of the eight cells defined by crossing Number of

Table 1. Mean RT and percent error rate for the physical and name identity tasks as a function of the number of items in the display

Task	Trial Type			
	Within-LVF	Within-RVF	Across-b-RVF	Across-b-LVF
Three-item trials				
Physical identity	424 (2.2)	426 (1.7)	441 (2.5)	446 (5.0)
Name identity	602 (7.4)	671 (7.8)	552 (5.0)	611 (5.3)
Four-item trials				
Physical identity	459 (2.9)	483 (2.9)	633(15.0)	676(15.1)
Name identity	894(11.7)	921(13.8)	835(13.8)	898(15.8)

Note. RTs in milliseconds; percent errors appear in parentheses.

Items (three or four) \times Task (PI, NI) \times Hand (right, left) for each participant. Then we entered the eight values for each participant into a repeated measures ANOVA. Of importance, there was a significant interaction between Number of Items \times Task [$F(1, 19) = 36.612, p < .0001$]. As in the raw RT data, across-hemisphere processing facilitated performance less on four-item trials than on three-item trials and this effect was more pronounced for the less complex PI task [$F(1, 19) = 132.565, p < .001$] than for the more complex NI task [$F(1, 19) = 4.265, p = .054$]. However, unlike the raw RT data, this effect was not only significant for the PI task but also marginally significant for the NI task. Thus, when differences in baseline RT were taken into account, the across-hemisphere advantage was smaller on four-item trials than on three-item trials for both the PI and the NI task (see Figure 3). As we show next, the analysis of error rate leads to the same conclusion.

Error Rate

As observed in the analysis of mean RT, there was a significant main effect of number of items [$F(1, 19) = 66.133, p < .0001$] because the error rate was higher on four-item trials (11.25%) than on three-item trials (4.48%). Also, as

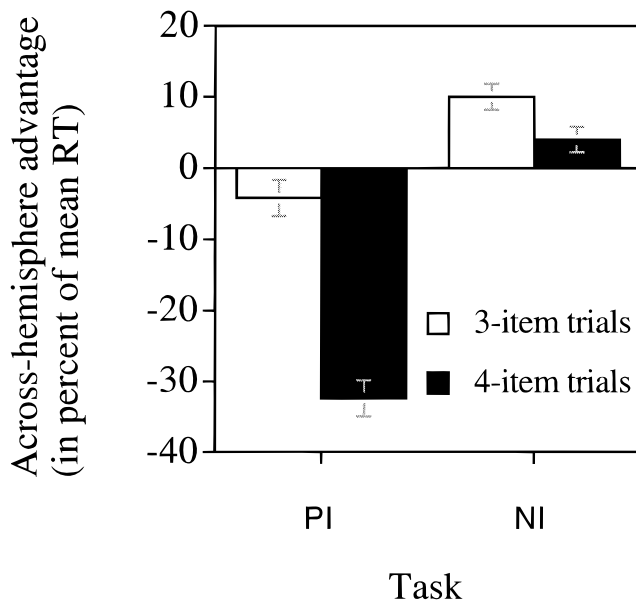


Fig. 3. The across-hemisphere advantage expressed as a percentage of mean RT as a function of task and the number of items in the display. Negative values indicate a within-hemisphere advantage. All values were calculated using the formula [within RT across RT]/overall mean RT]. Notice that across-hemisphere processing was more advantageous to performance for the NI task than for the PI task for both the three-item and the four-item displays. Of importance, across-hemisphere processing was significantly less advantageous to performance when the display contained four items than when there were only three, and this effect occurred for both the PI and the NI tasks. Error bars indicate standard error of the mean for each condition.

observed in the RT data, there was a significant main effect of task [$F(1, 23) = 13.123, p < .002$], because the error rate was higher for the NI task (10.05%) than for the PI task (5.68%). The interaction between Task \times Number of Items that appeared in the RT data was not significant in the analysis of error rate [$F(1, 19) = 1.067, p > .30$].

As in the analysis of mean RT, there was a significant main effect of trial type [$F(1, 23) = 6.894, p < .0001$] that was qualified by several significant interactions. Of most importance, there was a significant interaction between Number of Items \times Trial Type [$F(3, 57) = 13.720, p < .0001$]. As hypothesized, a planned contrast revealed that across-hemisphere processing facilitated performance more on three-item trials (0.60% across-hemisphere advantage) than on four-item trials (7.88% within-hemisphere advantage) [$F(1, 19) = 39.264, p < .0001$]. There was also a significant interaction between Task \times Trial Type [$F(1, 19) = 9.508, p < .0001$]. As in the RT data, a planned contrast revealed that across-hemisphere processing was significantly more advantageous to performance for the NI task (0.17% across-hemisphere advantage) than for the PI task [6.49% within-hemisphere advantage; $F(43.634), p < .0001$].

Finally, there was a marginally significant interaction between Number of Items \times Task \times Trial Type [$F(3, 57) = 2.652, p = .0572$]. Replicating the RT data, the degree to which IHI was advantageous to the performance of each task was smaller on four-item trials than on three-item trials and this effect was more pronounced for the PI task than for the NI task (see Figure 4). For the PI task, across-hemisphere processing was significantly less advantageous to performance on four-item trials than on three-item trials [$F(1, 19) = 60.442, p < .0001$] because the marginally significant 1.32% within-hemisphere advantage on three-item trials [$F(1, 19) = 3.397, p < .081$], became a highly significant 11.67% within-hemisphere advantage on four-item trials [$F(1, 19) = 64.964, p < .0001$]. For the NI task, across-hemisphere processing was also significantly less advantageous to performance on four-item trials than on three-item trials [$F(1, 19) = 7.520, p < .02$] because the 2.43% across-hemisphere advantage for the NI task that was present on three-item trials [$F(1, 19) = 12.968, p < .002$] became a nonsignificant 2.08% within-hemisphere advantage [$F(1, 19) = 2.040, p > .16$] on four-item trials.

GENERAL DISCUSSION

Both of our predictions were confirmed by the data. First, as hypothesized, our findings replicate prior work indicating that there is a shift toward greater interhemispheric efficiency as task complexity increases (e.g., Banich & Belger, 1990, Banich & Passarotti, 1999a; Belger & Banich, 1992, 1998, Copeland & Zaidel, 1996; Weissman & Banich, 1999; Yoshizaki & Tsuji, 1999). In the RT data (see Figure 3), the within-hemisphere advantage for the less complex PI task shifted to a significant across-hemisphere advantage for the more complex NI task. In the error rate data (see Figure 4), the lack of a significant difference between within- and

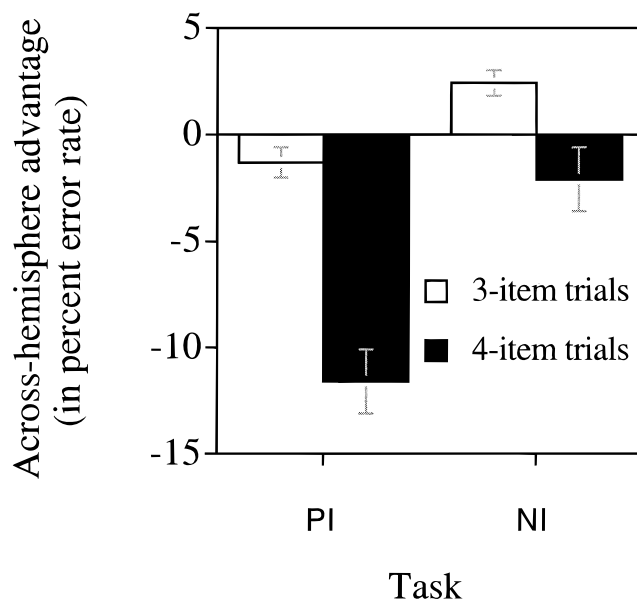


Fig. 4. The across-hemisphere advantage in percent error rate as a function of task and the number of items in the display. Negative values indicate a within-hemisphere advantage. As in the RT data, across-hemisphere processing was more advantageous to performance for the NI task than for the PI task for both the three-item and four-item displays. Of importance, across-hemisphere processing was significantly less advantageous to performance for each task when there were four items in the display as compared to just three. Error bars indicate standard error of the mean for each condition.

across-hemisphere trials for the PI task shifted to a significant across-hemisphere advantage for the NI task in the three-item displays. In the four-item displays, a large within-hemisphere advantage on the PI task shifted to a reduced and nonsignificant within-hemisphere advantage for the NI task. The crucial finding here is that whether or not an across-hemisphere advantage was observed for the NI task, interhemispheric processing was always more advantageous to performance for the NI task than for the PI task. This result is quite consistent with our model of IHI in which the benefits of dividing processing across two somewhat independent hemispheres begin to outweigh the costs of communication as task complexity increases.

An important implication of our results is that performance will be maximized if the degree to which IHI underlies performance varies dynamically with task demands. In particular, our data suggest that the performance of relatively simple tasks will be maximized by within-hemisphere processing, while the performance of more complex tasks will be optimized by across-hemisphere processing. In fact, several sources of data suggest that, when either within- or across-hemisphere processing can be used to perform a task, the degree to which across-hemisphere processing underlies performance does indeed vary as a function of processing demands. First, in a recent series of behavioral experiments (Weissman & Banich, 2000), we found that

performance in a midline condition (in which within- and across-hemisphere processing were equally possible) resembled that on within-hemisphere trials for the simpler PI task, for which there was a within-hemisphere advantage. However, performance on midline trials resembled that on across-hemisphere trials for the more complex NI task, for which there was an across-hemisphere advantage. Second, a number of neuroimaging studies have revealed that simpler tasks produce unilateral activation (which might reflect within-hemisphere processing) while more complex tasks produce bilateral activation (which might reflect across-hemisphere processing; e.g., Klingberg et al., 1997). Third, relative to younger adults, older adults show a benefit from IHI in behavioral studies at lower levels of task complexity (Reuter-Lorenz et al., in press) and exhibit greater bilateral activation in neuroimaging studies (e.g., Reuter-Lorenz et al., 1996). Thus, having both hemispheres involved in processing may be a processing strategy employed by the elderly brain to cope with diminished capacity (Reuter-Lorenz et al., in press). Clearly, all of these studies are consistent with the view that the degree to which IHI underlies performance varies with processing demands in a way that optimizes performance.

Our second prediction was also confirmed by the data. In particular, we found that IHI was less advantageous to the performance of each task when the hemispheres received equal numbers of inputs (i.e., in the four-item displays) than when they received unequal numbers of inputs (i.e., in the three-item displays). We suggest that IHI is more advantageous to performance when the hemispheres receive unequal numbers of items because, in this situation, across-hemisphere processing allows some of the critical information to be processed by a relatively unburdened hemisphere whose processing capacity is relatively less taxed.

Notice that our interpretation of the results relies heavily on the idea of capacity limitations of each hemisphere, and assumes that the hemispheres can operate at least to some degree in parallel, which allows the relatively unburdened hemisphere to process the information it receives somewhat independently of the more burdened hemisphere. Other data from our laboratory support such assumptions. In particular, we found that a division of processing was more advantageous when the hemispheres had to perform two operations rather than one (Banich & Passarotti, 1999b). In the OR condition, which required only one operation, individuals decided whether a lateralized target item matched any of four probes (two in each visual field) on the basis of *either* color or shape. In the AND condition, which required two operations, individuals decided whether the target item matched one probe in color and another in shape. The stimulus arrays used in both the OR and AND conditions were identical in that for match trials, there was always one match in color and another in shape. For the AND condition, there was a performance advantage when the probe matching in shape was located in one visual field and the probe matching in color was located in the opposite visual field, as compared to when both probes were positioned in the same visual

field. This finding suggests that dividing operations (i.e., shape matching and color matching) across the hemispheres so that each can be performed somewhat independently yields superior performance. In contrast, for the OR condition performance was superior when both matching probes were presented to the same rather than to opposite visual fields, suggesting that when only one operation needs to be performed, no advantage accrues from a division of processing.

One other aspect of the comparison between the three- and four-item arrays is worth noting. Although across-hemisphere processing was more advantageous for the three- than for the four-item arrays, equating the number of inputs to each visual field had differential effects for the PI and NI tasks in terms of the degree to which it reduced the efficiency of across-hemisphere processing. For the NI task, it reduced the across-hemisphere advantage by only 5% of mean RT. In contrast, for the PI task it reduced the across-hemisphere advantage by 28% of mean RT (see Figure 3). We speculate that because of the additional processing steps that must be performed on each input in the NI task, raising the number of inputs from three to four increased task complexity more for the NI task than for the PI task. Consistent with this speculation, the increase in RT associated with raising the number of inputs from three to four was much larger for the NI task (278 ms) than for the PI task (129 ms). In fact, the increase in RT for the NI task associated with raising the number of inputs from three to four (278 ms) was even larger than the increase in RT associated with performing the NI task relative to the PI task (250 ms). These data suggest the possibility that for the NI task, the reduction in the efficiency of across-hemisphere processing produced by equating the number of items to each hemisphere might have been partially offset by an increase in the utility of interhemispheric processing associated with a large increase in task complexity. Although a firm conclusion on this point must await further investigation, our findings clearly indicate that whether or not the hemispheres receive equal numbers of inputs is an important variable that needs to be included in future models of how IHI modulates performance (e.g., Banich, 1995; Banich & Belger, 1990).

If, as we suggested earlier, the degree to which IHI underlies task performance varies to maximize performance, then our finding that IHI facilitates performance less when the hemispheres receive equal numbers of inputs than when they receive unequal numbers of inputs has an important implication. In particular, our finding suggests that across-hemisphere processing is likely to underlie performance more when the hemispheres are differentially burdened (i.e., when IHI is relatively advantageous to performance) and less when they are equally burdened (i.e., when IHI is not as advantageous to performance).

In sum, our present findings contribute to an emerging picture of IHI as a flexible mechanism whose role in task performance changes dynamically with processing demands. Future studies should investigate how this flexibility is achieved and the specific conditions under which a

distribution of processing across the hemispheres occurs. Finally, it would also be interesting to determine which processing stages are divided across the hemispheres and whether the neural correlates of such a division can be localized with functional neuroimaging techniques.

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