

Interhemispheric Interaction During Global–Local Processing in Mathematically Gifted Adolescents, Average-Ability Youth, and College Students

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Interhemispheric interaction in mathematically gifted (MG) adolescents, average-ability (AA) youth, and college students (CS) was examined by presenting hierarchical letter pairs in 3 viewing conditions: (a) unilaterally to the right hemisphere (RH), (b) unilaterally to the left hemisphere (LH), or (c) bilaterally, with 1 member of the pair presented to each hemisphere simultaneously. Participants made global–local, match–no-match judgments. For the AA and CS, the LH was faster for local matches and the RH for global matches. The MG showed no hemispheric differences. Also, AA and CS were slower on cooperative compared with unilateral trials, whereas the MG showed the opposite pattern. These results suggest that enhanced interhemispheric interaction is a unique functional characteristic of the MG brain.

Functional asymmetry and processing specialization of the left hemisphere (LH) and right hemisphere (RH) are well-documented characteristics of the human brain (Hellige, 1993a). Yet, as compelling as these hemispheric processing propensities may be, the brain does not consist of two hemispheres operating in isolation. In fact, the different cognitive specialties of the LH and RH are so well integrated that they seldom cause significant processing conflicts in neurologically normal individuals. Thus, hemispheric specialization cannot be conceptualized as a static difference in the processing capacity of two independent and isolated hemispheres, but rather consists of a dynamic interactive partnership between the two (Banich, 1995; Hellige, 1993b, 2000; Liederman, 1998; Zaidel, 1995). For these reasons, numerous investigations have focused on how two functionally distinct cerebral hemispheres contribute to a whole-brain processing system, one that is devoted to the production of unified cognitions and behaviors. Of particular importance has been the identification of the precise conditions under which the two hemispheres coordinate their differing processing propensities and capacities to optimize performance (Banich & Shenker, 1994). As suggested by Hellige (1993a), having learned so much about hemispheric differences (and independence), it is now time to “put the brain back together again” (p. 206).

Current research on individual differences in hemispheric laterality has consistently suggested that variations in the functional organization of the brain and its interactive properties may be related to individual differences in cognitive abilities (Hellige,

1993a; O'Boyle, 2000; O'Boyle & Hellige, 1989). For example, there is growing evidence that the mathematically gifted (MG) brain may be functionally organized in a qualitatively different manner compared with those of average math ability (AA; O'Boyle et al., 2002). Specifically, enhanced development and subsequent processing reliance on the specialized capacities of the RH, coupled with a fine-tuned ability for rapid and coordinated exchange of information between the hemispheres, are hypothesized to be unique processing characteristics of the MG brain (O'Boyle, 2000; O'Boyle et al., 2002).

Support for a special form of cerebral organization characterizing the MG has come from a variety of investigative sources. Benbow (1986, 1988) has reported that MG children (i.e., scoring at least 700 on the Scholastic Aptitude Test [SAT] Math portion before age 13, placing them in the top 0.5% in numerical ability) are typically male, left handed, and myopic and have a higher than average incidence of allergy, migraine, and other immune disorders. In keeping with the tenets of the Geschwind and Galaburda (1987) model of cerebral dominance, Benbow proposed that this collection of physiological correlates is suggestive of enhanced RH development (perhaps as a by-product of prenatal testosterone exposure) and is a biological prerequisite for exceptional mathematical ability. The logic here is that heightened development of the RH enhances visuospatial capacity, a known predictor of superior mathematical reasoning ability (Benbow, 1988).

Since this early suggestion, a series of empirical studies have produced findings consistent with the notion of enhanced RH functioning and heightened interhemispheric collaboration in the MG, especially for males. O'Boyle and Benbow (1990) investigated this issue using a dichotic listening task and a free-vision chimeric face task, testing both MG and AA participants (all right-handed and 12 to 14 years old) for patterns of brain laterality. In their first experiment, both groups performed a dichotic listening for syllables task that in previous research (Hellige & Wong, 1983) had produced a robust right-ear advantage, reflecting lateralization of the language faculties to the LH. O'Boyle and Benbow predicted the AA would show the prototypic LH superiority for this task, whereas the MG would show little asymmetry or perhaps

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even an RH advantage. This prediction was based on the logic that if the RH of the MG is more highly developed (dominant), then it will play a greater role during information processing. In keeping with their hypothesis, O'Boyle and Benbow found that the AA exhibited the prototypic LH advantage, whereas the MG showed no hemispheric asymmetry (i.e., they were equally able to identify the syllables with either ear). This pattern suggests that the RH of the MG is unusually engaged and relied upon during information processing, even for the analysis of linguistic stimuli. Additionally, it may also reflect a special form of brain bilateralism such that the MG are more readily able to exchange (and integrate) information between the hemispheres without the usual processing penalties or costs.

In a second experiment, O'Boyle and Benbow (1990) used the free-vision chimeric face task (CFT) developed by Levy et al. (e.g., Levy, Heller, Banich, & Burton, 1983) to examine the degree of RH processing engagement by the MG. In the CFT participants view pairs of chimeric faces and judge which of the two appears to be happier. The dependent variable is the number of times the left-side smile/right-side neutral composite is chosen compared with its mirror image. On the basis of previous research suggesting that the RH is primarily responsible for processing human faces and the determination of their emotional affect (Levy et al., 1983), O'Boyle and Benbow predicted that both the MG and the AA would show an RH bias in their performance (i.e., a larger percentage of left-side smile/right-side neutral composites being chosen as the happier face), but the MG would exhibit an even stronger bias because of their enhanced RH functioning. The results revealed the MG did indeed choose the left-side smile/right-side neutral composites significantly more often than the AA, a pattern indicative of greater involvement and processing reliance on the RH. Interestingly, O'Boyle and Benbow correlated the degree of RH processing as indexed by their CFT score, that is, a laterality quotient computed as $(R - L)/N$, with their SAT score (R = number of times the right-side smiling face was chosen, L = the number of times the left-side smiling face was chosen, and N = the total number of trials). This correlation was significant and suggested that the greater the RH processing engagement when performing the CFT, the higher the SAT score. This finding lends further support to the notion that enhanced RH functioning plays an important role in mediating mathematical giftedness.

O'Boyle, Gill, Benbow, and Alexander (1994, Experiment 1) further converged on the idea of enhanced RH processing and heightened interhemispheric collaboration in the MG by using a concurrent finger-tapping paradigm. Twenty-four MG and 16 AA males tapped a keypad for 10 s (first with one hand, then the other) while either remaining silent (baseline) or reading a paragraph aloud (concurrent verbal load). The logic used in this finger-tapping task is that, during the processing of the concurrent verbal load, the LH is forced to split its cortical processing resources between reading the paragraph (a linguistic task) and motor control of the right hand (an LH-mediated motor task). This trade-off leads to a reduction in right-hand tapping rate relative to baseline (i.e., tapping with no concurrent verbal load). Left-hand tapping rate is unaffected by a concurrent verbal task because the RH bears little or no responsibility for the processing of the linguistic load (Kinsbourne & Hiscock, 1983). In light of their hypotheses regarding the brain characteristics of the MG, O'Boyle et al. predicted that the MG would exhibit a reduction in tapping rate for both hands,

whereas the AA would show only the prototypic right-hand tapping reduction. This was exactly the pattern obtained, providing converging evidence for the idea that the RH of the MG plays an enhanced role during information processing. This pattern is also consistent with the notion of enhanced interhemispheric cooperation in the MG, with each of the hemispheres being equivalently engaged and contributing equally to task performance.

These results are buttressed by additional experiments conducted by O'Boyle, Alexander, and Benbow (1991) and O'Boyle, Benbow, and Alexander (1995), who reported direct physiological measurements showing that the RH was more active in the MG, as well as evidence of enhanced interhemispheric collaboration. In the O'Boyle et al. (1991) study, participants were asked either to gaze at a blank slide (baseline) or to judge which of two chimeric faces appeared happier, while corresponding electroencephalographic (EEG) activity was monitored at four brain sites (i.e., frontal, temporal, parietal, and occipital lobes) over the RH and LH. O'Boyle et al. made two predictions. At the behavioral level, they expected to replicate their earlier CFT results, with the MG more often choosing the left-side smile/right-side neutral composites as the happier face. At the physiological level, they expected the MG to exhibit significantly greater RH activation, with a propensity toward bilateral engagement of the hemispheres. Their results revealed that, while looking at a blank slide (i.e., baseline), the MG were primarily LH active. During the CFT, however, they shifted to focalized engagement of the right frontal and temporoparietal areas, activating the very regions required for judgments concerning the emotional content of a face (Banich, 1997). In contrast, the AA were as likely to shift right as left, anteriorly as posteriorly. This ambiguous pattern may reflect a less developed, more immature state of functional cerebral organization in the AA (cf. Moses et al., 2002). These findings led O'Boyle et al. to conclude that the MG were better able to access, coordinate, and implement the cortical resources of the RH during information processing (O'Boyle & Gill, 1998) and that the MG brain is characterized by a unique capacity to rapidly switch activation from one region (hemisphere) to another, as evidenced by their ability to shift from LH activation at rest to focalized RH activation during CFT performance.

The idea of a highly integrated form of bilateralism as a unique processing characteristic of the MG brain has received additional support from a neuroimaging study. O'Boyle et al. (2002) used functional magnetic resonance imaging to monitor brain activation in a group of MG while mentally rotating Shepard and Metzler (1971) block figures. They found the MG to be significantly more active overall compared with matched AA participants (a finding suggestive of heightened processing capacity), and the MG were more bilaterally engaged in contrast to the AA, who were more unilaterally (and predominantly RH) involved.

These findings indicate that enhanced involvement of the RH during information processing is a unique characteristic of the MG brain, and there is emerging evidence that a highly integrated form of hemispheric collaboration may subservise this heightened RH contribution. However, no previous research specifically examines whether the MG differ from their AA counterparts in the nature and relative efficiency of their interhemispheric interaction. Thus, the current study focuses on the pattern of hemispheric specialization in a group of MG male adolescents and the extent to which they are able to cooperatively exchange information between the

hemispheres during global–local judgments of hierarchical letter stimuli. On the basis of previous research (Robertson, Lamb, & Zaidel, 1993), we expected that the AA as well as a group of average-ability college students (CS) would show the prototypic RH–global versus LH–local processing advantages and would be slower and less accurate in their ability to exchange such information between the hemispheres. In contrast, given their hypothesized enhanced RH functioning and propensity toward heightened interhemispheric collaboration, it was anticipated that the MG would show a reduced level of global–local processing asymmetry and faster, more accurate exchange and integration of such information between the hemispheres.

Method

Participants

Sixty right-handed males (18 MG, 18 AA, and 24 CS) participated in the experiment. Hand dominance was assessed using a modified version of the Edinburgh Handedness Inventory (Oldfield, 1973) containing eight items designed to determine the hand used when writing, drawing, and throwing; when using a scissors, a toothbrush, a knife without a fork, and a spoon; and when striking a match. All participants responded “usually right” or “always right” to six of the eight tasks and always reported writing with their right hand.

MG participants were recruited from the Challenges for Youth-Talented program at Iowa State University. All had completed the 7th or 8th grade, and their mean age was 13.7 years. The mean SAT Math score for the MG was 620 ($SD = 73$, range = 540–760). (Note that the minimum SAT Math score for college-bound seniors is 200, the maximum is 800, and the average is 500; see Stanley & Benbow, 1983.) AA participants were recruited from the Ames Iowa Middle School and from the local Boys Club. Members of the AA group had completed the 7th or 8th grade, and their mean age was 13.1 years. No one in the AA control group had taken the SAT Math exam, nor did they report taking any advanced mathematics classes in school. The 24 right-handed CS participants (mean age = 20.3 years) were selected from the Psychology Department participant pool.

Self-report was used to screen participants for neurological damage or disorder, developmental disabilities, impaired eyesight, and current medication use. Two MG and 3 AA participants were excluded from the study using this preliminary screening procedure. Informed consent was obtained from each participant (and parents) prior to the study. The MG and the AA were paid \$7.50; the CS participated in exchange for extra course credit.

Stimulus Materials

The stimuli consisted of black vertical pairs of hierarchical (compound) letters on a white background and were constructed using Microsoft Paintbrush software. The global letters measured 2.7 cm high \times 3.0 cm wide, and the local letters composing these global letters were 0.5 cm high \times 0.5 cm wide. At a viewing distance of 45 cm, the vertical pairs of global letters subtended a visual angle of 7.39 degrees vertically and 3.09 degrees horizontally, and the local letters subtended a visual angle of 0.64 degrees vertically and 0.64 degrees horizontally. On unilateral trials, the innermost edge of the hierarchical pair appeared 3.10 degrees (8.5 cm) to the right or left of fixation. On bilateral cooperative trials, at a viewing distance of 45 cm, the single hierarchical letters subtended a visual angle of 3.18 degrees vertically and 3.09 degrees horizontally and were 3.10 degrees to the left and right of fixation.

Eight hierarchical patterns adapted from Robertson et al. (1993) were used in the experiment. The stimulus set was composed of the capital (global) letters *H*, *S*, *R*, and *E* made up of smaller local elements (again the letters *H*, *S*, *R*, and *E*). Four patterns had the same letters at the global and

local levels and were thus “consistent.” These were composed of a global *H*, *S*, *R*, and *E* created from local *H*s, *S*s, *R*s, and *E*s, respectively. Four patterns had different letters and were thus “inconsistent.” They were composed of a global *H* created from local *S*s, a global *S* created from local *H*s, a global *R* created from local *E*s, and a global *E* created from local *R*s. Both the consistent and inconsistent forms of the letters *H* and *S* were then paired with themselves and with each other (a total of eight combinations). Likewise, both the consistent and inconsistent forms of the letters *R* and *E* were paired with themselves and each other (a total of 8 combinations), yielding a combined set of 16 hierarchical letter pairs. An additional 16 pairs were then constructed using these same letter stimuli but with either their spatial locations reversed (i.e., on unilateral trials, the letter on the top was now on the bottom and vice versa) or their visual fields of presentation reversed (i.e., on bilateral trials, the letter on the left was now on the right and vice versa). Thus, 32 pairs of hierarchical letters were created in total, with 16 matching at the global level and 16 matching at the local level.

Apparatus

The Micro Experimental Laboratory (MEL) software program (Schneider, 1988) was used in conjunction with a microcomputer and VGA color monitor to present the stimuli, control exposure times, and collect accuracy and response latency data. The experiment was run under microcomputer control, and luminance and contrast were held constant over the duration of the experiment. The computer keys *J* (match) and *K* (mismatch) were used to register responses.

Procedure

On each trial, the participant focused on a central fixation point (an asterisk) and then pressed the space bar on the computer keyboard when ready to proceed (the other hand was used for responding to the stimuli). One second later, in the unilateral condition, two hierarchical letters were projected one above the other to either the left visual field (LVF)–RH or the right visual field (RVF)–LH. In the bilateral cooperative condition, one hierarchical letter was presented in each visual field simultaneously, with one projecting to the LVF–RH and the other to the RVF–LH. Examples of each stimulus type are illustrated in Figure 1. In all instances, stimulus exposure time was 160 ms. Participants were instructed to decide whether the two figures matched or mismatched based on either their global configuration or the local elements composing them. Thus, when individuals were looking for global matches, they were ignoring local elements and vice versa. This was a between-blocks manipulation. The microcomputer was preprogrammed to record errors and response latencies.

Data were collected in two blocks of 120 trials for each condition (i.e., global and local), and there were two sets within each block containing 60 trials. Twenty trials were presented in each viewing condition (LVF, RVF, bilateral) with their order randomized. Letter stimuli were randomly selected for each trial, with the constraint that half of the trials in each viewing condition would match. At the beginning of each set, participants changed their hand of response followed by 10 practice trials. Half of the participants started with the left hand (match) and the other half with the right hand (match). Half of the participants started with global processing trials and the other half with local processing trials. Participants were told to respond as quickly and accurately as possible.

Results

Reaction Time Data

Table 1 shows the mean reaction times (RTs) for correct responses by group, level, and viewing condition. Data from 1 AA and 1 CS participant were excluded from the analysis because their

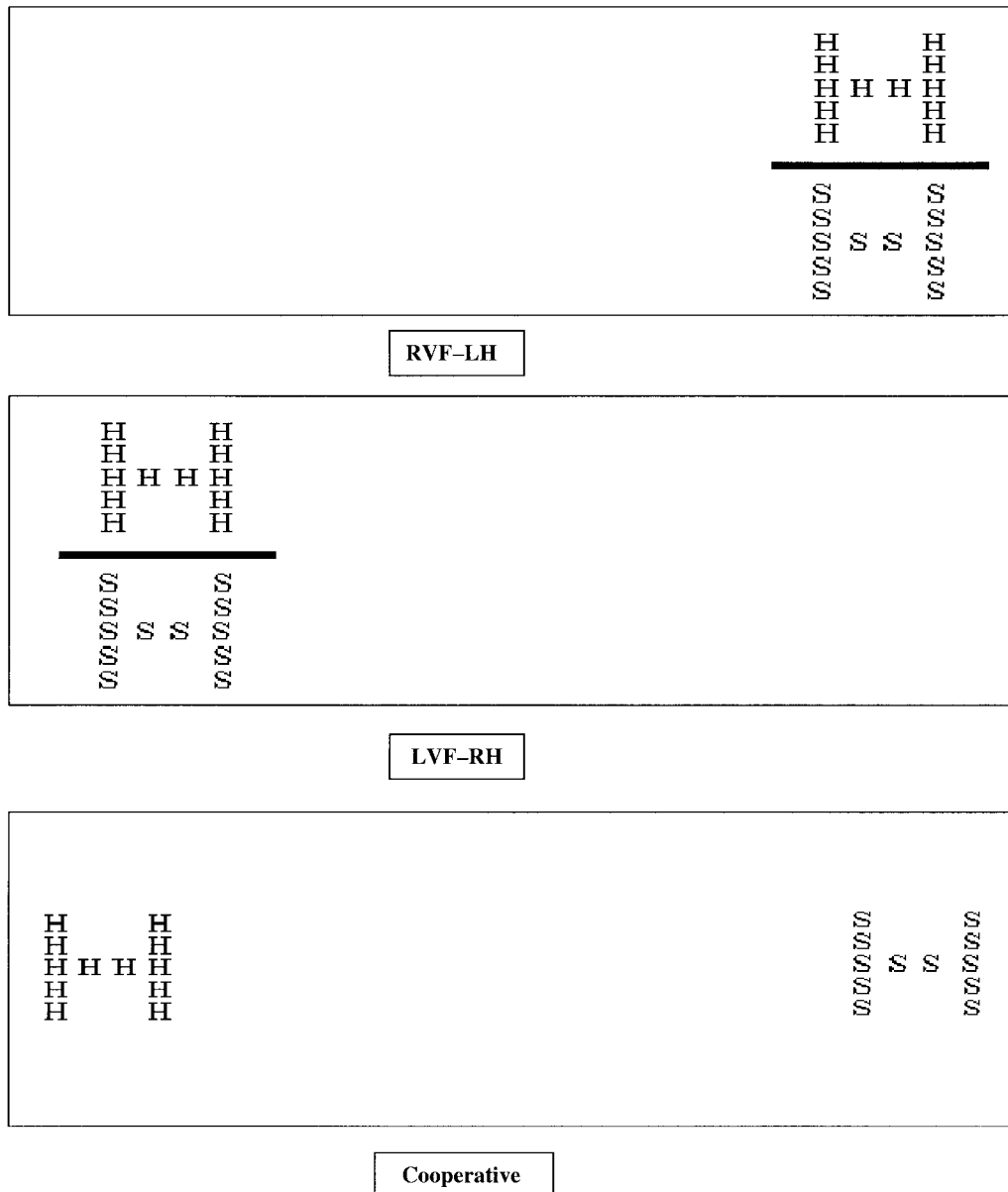


Figure 1. Examples of each trial type. Top: Right visual field (RVF)–left hemisphere (LH). Middle: Left visual field (LVF)–right hemisphere (RH). Bottom: Bilateral cooperative.

error rate exceeded 75%. For all participants RTs less than 250 ms or greater than 3,500 ms were considered outliers and discarded (less than 5% of the data). Preliminary analyses including hand of response (left, right) and trial type (consistent, inconsistent) showed that for all three groups, RT for the right hand was somewhat faster than for the left hand, and there was a significant time advantage for consistent compared with inconsistent trials but only for local (not global) processing. However, hand and trial type did not interact significantly with any other variable and so were not included in the main analyses.

Mean RTs for correct responses were evaluated using a 3 (group: MG, AA, CS) \times 2 (level: global, local) \times 3 (visual field: LVF, RVF, cooperative) mixed-design analysis of variance

(ANOVA), with group as a between-subjects factor and level and visual field as within-subject factors. The results of this analysis revealed a significant main effect for level, $F(1, 57) = 46.66$, $MSE = 1,599$, $p < .01$, with global responses (932 ms) quicker than local responses (1,023 ms). There was also a significant main effect of group, $F(2, 57) = 3.56$, $MSE = 76,022$, $p < .05$. Comparisons among the means using the Bonferroni procedure showed that the MG (929 ms) were significantly faster than the AA (1,029 ms). However, the CS (975 ms) were not significantly different from either the AA or the MG. There was a significant main effect for visual field, $F(2, 114) = 63.22$, $MSE = 1,188$, $p < .01$, that was qualified by a statistically reliable Group \times Visual Field interaction, $F(4, 114) = 18.66$, $MSE = 1,370$, $p < .01$. The

Table 1
Mean Reaction Times (in Milliseconds) for Different Groups and for Each Experimental Condition

Group	LVF–RH		RVF–LH		Cooperative	
	M	SD	M	SD	M	SD
Global processing						
Math gifted	843	140	856	160	810	156
Average ability	952	173	948	185	970	189
College students	840	96	903	134	863	139
Local processing						
Math gifted	1,038	148	1,034	163	991	135
Average ability	1,105	194	1,051	222	1,145	187
College students	1,092	134	1,020	153	1,133	193

Note. LVF = left visual field; RH = right hemisphere; RVF = right visual field; LH = left hemisphere.

three-way Group × Level × Visual Field interaction was also significant, $F(4, 114) = 2.42, MSE = 1,685, p < .01$.

The three-way interaction was first examined in terms of between-group differences. A one-way ANOVA was conducted for each visual field and level combination, with group as a between-subjects factor. There was a reliable group effect for the global cooperative condition, $F(2, 57) = 4.64, MSE = 18,696, p < .02$. There was also a group effect for the local cooperative condition, $F(2, 57) = 4.44, MSE = 30,954, p < .02$. None of the unilateral conditions showed any significant group effects. Comparisons using a post hoc Bonferroni procedure showed that the MG were significantly faster than both the AA and the CS in the cooperative condition at both the global and the local levels. The CS and the AA did not differ from each other in the cooperative condition.

The three-way interaction was also examined for visual field differences within each group by paired sample *t* tests. For the CS, the LVF–RH was faster than the RVF–LH for global trials, $t(23) = 2.01, SE = 32.38, p < .05$, and the RVF–LH was faster than the LVF–RH for local trials, $t(23) = 2.93, SE = 39.15, p < .01$. Thus, the differences found on unilateral trials were consistent with our predictions and the prevailing global–local literature. The RVF–LH unilateral condition was significantly slower than the bilateral cooperative condition, $t(23) = 2.32, SE = 40.73, p < .01$, at the global level. At the local level, the unilateral RVF–LH condition was significantly faster than the bilateral cooperative condition, $t(23) = 2.25, SE = 49.94, p < .01$. There was no significant difference between the LVF–RH and the cooperative viewing condition for either global or local judgments.

The AA were faster with the RVF–LH than the LVF–RH for local trials, $t(17) = 1.93, SE = 29.90, p < .05$, but there was no difference between the unilateral presentation conditions for global trials. None of the comparisons between unilateral and bilateral cooperative conditions were statistically reliable for the AA, although there was some evidence of LH specialization for local processing.

The MG did not show any differences on unilateral trials (i.e., there was no difference between LVF–RH and RVF–LH performance at either the global or local levels). However, the cooperative condition was faster than the RVF–LH, $t(17) = 2.98,$

$SE = 23.05, p < .01$, and the LVF–RH, $t(17) = 2.67, SE = 19.58, p < .01$, for global-level processing. The cooperative condition was also faster than the RVF–LH, $t(17) = 2.30, SE = 33.08, p < .01$, and the LVF–RH, $t(17) = 2.01, SE = 23.33, p < .01$, for local-level processing. Importantly, this pattern is qualitatively different from that found in the CS and the AA groups because the MG were significantly faster in the bilateral cooperative condition compared with both unilateral conditions, whereas the AA and the CS were not.

Error Data

Mean numbers of errors (of 40) are shown in Table 2 as a function of group, level, and visual field. Error data were evaluated using a 3 (group: MG, AA, CS) × 2 (level: global, local) × 3 (visual field: LVF, RVF, cooperative) mixed-design ANOVA, with group as a between-subjects factor and level and visual field as within-subject factors. The analysis revealed a significant main effect for level, $F(1, 57) = 26.70, MSE = 301.3, p < .01$, with the local level (9.5) producing more errors than the global level (6.7). There were no other significant main effects or interactions involving error rates. When considered with the RT data, there was no indication of a speed–accuracy trade-off.

Discussion

The current study was designed to determine whether the functional brain organization of the MG was different either qualitatively or quantitatively from the AA or CS. For this purpose, we used unilateral and bilateral presentations of hierarchical letter stimuli. In the cooperative condition, inputs were divided between the visual fields so that each hemisphere had access to only half of the information necessary to perform the task, providing an index of interhemispheric collaboration. Thus, comparisons between LVF and RVF unilateral presentations allow for an analysis of hemispheric specialization, whereas those between unilateral and cooperative presentations allow for an analysis of interhemispheric processes (Banich & Shenker, 1994).

Table 2
Mean Numbers of Errors (of 40) for Different Groups and for Each Experimental Condition

Group	LVF–RH		RVF–LH		Cooperative	
	M	SD	M	SD	M	SD
Global processing						
Math gifted	4.4	2.4	6.8	2.5	7.4	3.1
Average ability	5.4	2.5	7.8	2.4	8.4	3.2
College students	4.2	2.3	6.7	2.2	7.1	2.8
Local processing						
Math gifted	10.0	3.4	8.5	3.2	9.7	4.7
Average ability	12.1	3.5	9.8	4.6	13.6	5.2
College students	9.3	3.5	7.5	3.1	12.6	4.9

Note. LVF = left visual field; RH = right hemisphere; RVF = right visual field; LH = left hemisphere.

The CS produced the prototypic results for global–local judgments, with the RH superior for global processing and the LH for local processing (Robertson et al., 1993; Van Kleeck, 1989). The CS were especially poor in the local cooperative condition, which required between-hemispheres comparisons of small letters. In addition, although the AA displayed the prototypic results for local processing, they showed no significant difference between the LH and RH for global processing. This result is congruent with those of other studies (e.g., Christman & Weiner, 1997) reporting lateralization for local but not global analysis. Global processing is considered to be somewhat easier than local processing (e.g., Kimchi, 1988; Navon, 1977), and this was evident in the current experiment. Previous studies have also demonstrated that most hemispheric advantages are enhanced as task complexity is increased because the extended time frame required for processing a difficult task allows greater opportunity for a significant hemispheric asymmetry to emerge (Banich & Shenker, 1994; Hellige, 1993a; Weissman & Banich, 2000). In the current study, older CS participants did show hemispheric asymmetry for global processing presumably because they are more developmentally advanced, with hemispheres more specialized than those of the typical AA youth.

Although performance of the CS and the AA are of interest, the main focus of the study was the MG. The patterns produced by the CS and the AA functioned primarily as an interpretive backdrop. Our results illustrate that when inputs and processing resources are divided between the hemispheres, the MG outperform the AA and the CS. In fact, the MG were best when global–local information was divided between the hemispheres and interhemispheric communication was essential to completing the matching task. This finding is intriguing because the CS and AA did not show a processing advantage for the bilateral cooperative condition compared with the unilateral conditions; the MG were simply better at processing bilateral cooperative inputs.

As described earlier, previous studies have shown the MG to exhibit enhanced reliance on the RH during information processing. In the current study, there was some evidence of heightened RH involvement for local processing. In the latter condition, the prototypic effect is for the LH to be superior to the RH, as was found in both the AA and the CS. The MG, however, were equally able at performing local matches with either hemisphere, suggesting that both are actively engaged and equivalently capable of processing local information. The MG also failed to show the usual RH processing superiority for global processing. In light of previous research, one might have expected an enhanced RH asymmetry when performing global matches. The absence of this effect, however, may be a reflection of the extent to which the brain of the MG is interhemispherically integrated, relying on processing resources from both hemispheres irrespective of the nature of the stimuli to be analyzed or the hemisphere specialized for the task.

This result is also compatible with the notion that the MG can activate (or inhibit) regions in either the LH or RH that are crucial (or not) to processing hierarchical stimuli. In earlier EEG studies (O'Boyle et al., 1991, 1995), we found that MG males could selectively inhibit cortical regions not critical to task performance. For example, in the EEG–CFT experiment, the MG showed not only greater RH involvement but also significant LH inhibition. The latter may serve to insulate the RH from disruptive interhemispheric cross talk. By way of speculation, it may be that the corpus

callosum (CC) is a particularly important communication and control channel in the MG brain, with the regulation of information flow by means of this anatomical conduit aiding in the ability to selectively activate (or inhibit) different cortical regions depending on processing requirements.

Interestingly, Benbow (1986) has reported that left-handedness is more prevalent in the MG, which led to the O'Boyle and Benbow (1990) studies demonstrating that the MG are characterized by enhanced RH development, as suggested by the Geschwind and Galaburda (1987) cerebral dominance model. Moreover, research into the morphology of the CC has found that left-handers (who are overrepresented in the MG) have a larger CC compared with right-handers (Driesen & Raz, 1995; Witelson, 1985). Thus, an additional speculation may be that the MG perform better during the bilateral cooperative condition because their interhemispheric interaction is more efficient, perhaps relating to a difference in the size and shape of their CC. This would be consistent with the fact that the number of interhemispheric connections between cortical areas is proportional to CC size (Aboitiz, Scheibel, Fisher, & Zaidel, 1992; Clarke & Zaidel, 1994) and that overall CC volume exerts an influence on the speed and type of information transfer occurring among cortical areas (Hoptman & Davidson, 1994).

Should such speculations about CC differences in the MG prove correct, then MG adults might also show enhanced RH engagement and more efficient interhemispheric communication. We conducted a pilot study of 5 mathematically talented young adults using the current global–local task (4 of the participants were graduate students at the 99th percentile on the quantitative portion of their Graduate Record Examination). Their pattern was similar to that of the MG in that they performed better in the cooperative compared with unilateral conditions. Additionally, and consistent with the current study, no hemispheric specialization for global–local processing was found in these older MG types. That a similar result was obtained from high-ability young adults and MG adolescents suggests that they have a comparable functional brain organization.

The findings of the current study reinforce our hypothesis that superior coordination of cortical resources between the hemispheres is a unique processing characteristic of the MG brain. Our results also suggest that such enhanced interhemispheric collaboration (perhaps by means of the CC) increases the efficiency of MG brain functioning when the hemispheres are forced to cooperate during information processing. In the future, the CC may come to be regarded as one neural structure that differentiates the MG from those with average math ability, although this speculation requires further research to confirm.

Notably, the MG showed no reliable left–right differences when processing global or local information on unilateral trials. However, in the bilateral cooperative condition, MG RT was considerably faster compared with unilateral trials for both global and local processing. According to Elman et al. (1998), the RH plays a prominent role when information has to be integrated in the brain, and our previous research (O'Boyle et al., 1995) with the MG has shown their RH to be dominant during information processing. One further speculation may be that the MG are better during the bilateral condition because this cooperative type of input most closely matches their preferred processing style (i.e., efficient use of resources by means of a fully interconnected brain),

in which each hemisphere (particularly the RH) processes information according to its own specialization, and the subsequent products are bilaterally shared (and integrated) across the hemispheres without processing penalty. Thus, the current study provides additional support for the notion that the MG are better at relaying and integrating information between the cerebral hemispheres and that this enhanced interhemispheric collaboration is a unique functional characteristic of the MG brain.

References

- Aboitz, F., Scheibel, A. B., Fisher, R. S., & Zaidel, E. (1992). Individual differences in brain asymmetries and fiber composition in the human corpus callosum. *Brain Research, 598*, 154–161.
- Banich, M. T. (1995). Interhemispheric interaction: Mechanisms of unified processing. In F. L. Kitterle (Ed.), *Hemispheric communication: Models and mechanisms* (pp. 271–300). Hillsdale, NJ: Erlbaum.
- Banich, M. T. (1997). *Neuropsychology: The neural bases of mental function*. New York: Houghton Mifflin.
- Banich, M. T., & Shenker, J. I. (1994). Investigation of interhemispheric processing: Methodological considerations. *Neuropsychology, 8*, 263–277.
- Benbow, C. P. (1986). Physiological correlates of extreme intellectual precocity. *Neuropsychologia, 24*, 719–725.
- Benbow, C. P. (1988). Sex differences in mathematical reasoning ability in intellectually talented preadolescents: Their nature, effects, and possible causes. *Brain and Behavioral Sciences, 11*, 169–232.
- Christman, S. D., & Weiner, R. H. (1997). Hemispheric processing of form versus texture at the local level of hierarchical patterns. *Acta Psychologica, 96*, 193–206.
- Clarke, J. M., & Zaidel, E. (1994). Anatomical-behavioral relationships: Corpus callosum morphometry and hemispheric specialization. *Behavioural Brain Research, 64*, 185–202.
- Driesen, N. R., & Raz, N. (1995). The influence of sex, age, and handedness on corpus callosum morphology: A meta-analysis. *Psychobiology, 23*, 240–247.
- Elman, J. L., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1998). *Rethinking innateness*. Cambridge, MA: MIT Press.
- Geschwind, N., & Galaburda, A. M. (1987). *Cerebral lateralization*. Cambridge, MA: MIT Press.
- Hellige, J. B. (1993a). *Hemispheric asymmetry*. Cambridge, MA: Harvard University Press.
- Hellige, J. B. (1993b). Unity of thought and action: Varieties of interaction between the left and right cerebral hemispheres. *Current Directions in Psychological Science, 2*, 21–25.
- Hellige, J. B. (2000). All the king's horses and all the king's men: Putting the brain back together again. *Brain and Cognition, 42*, 7–9.
- Hellige, J. B., & Wong, T. M. (1983). Hemispheric-specific interference in dichotic listening: Task variables and individual differences. *Journal of Experimental Psychology: General, 112*, 218–239.
- Hoptman, M. J., & Davidson, R. J. (1994). How and why do the two cerebral hemispheres interact? *Psychological Bulletin, 116*, 195–219.
- Kimchi, R. (1988). Selective attention to global and local levels in the comparison of hierarchical patterns. *Perception and Psychophysics, 43*, 189–198.
- Kinsbourne, M., & Hiscock, M. (1983). Asymmetries of dual task performance. In J. B. Hellige (Ed.), *Cerebral hemisphere asymmetry: Method, theory and application* (pp. 253–334). New York: Praeger.
- Levy, J., Heller, W., Banich, M., & Burton, L. (1983). Perceptual asymmetry in free-viewing of chimeric faces. *Brain and Cognition, 2*, 404–419.
- Liederman, J. (1998). The dynamics of interhemispheric collaboration and hemispheric control. *Brain and Cognition, 36*, 193–208.
- Moses, P., Roe, K., Buxton, R., Wong, E., Frank, L., & Styles, J. (2002). Functional MRI of global and local processing in children. *NeuroImage, 16*, 415–424.
- Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9*, 353–383.
- O'Boyle, M. W. (2000). A new millennium in cognitive neuropsychology research: The era of individual differences. *Brain and Cognition, 42*, 135–138.
- O'Boyle, M. W., Alexander, J. E., & Benbow, C. P. (1991). Enhanced right hemisphere activation in the mathematically precocious: A preliminary EEG investigation. *Brain and Cognition, 17*, 138–153.
- O'Boyle, M. W., & Benbow, C. P. (1990). Enhanced right hemisphere involvement during cognitive processing may relate to intellectual precocity. *Neuropsychologia, 28*, 211–216.
- O'Boyle, M. W., Benbow, C. P., & Alexander, J. E. (1995). Sex differences, hemispheric laterality, and associated brain activity in the intellectually gifted. *Developmental Neuropsychology, 11*, 415–443.
- O'Boyle, M. W., & Gill, H. S. (1998). On the relevance of research findings in cognitive neuroscience to educational practice. *Educational Psychology Review, 10*, 397–409.
- O'Boyle, M. W., Gill, H. S., Benbow, C. P., & Alexander, J. E. (1994). Concurrent finger-tapping in mathematically gifted males: Evidence for enhanced right hemisphere involvement during linguistic processing. *Cortex, 30*, 519–526.
- O'Boyle, M. W., & Hellige, J. B. (1989). Cerebral hemisphere asymmetry and individual differences in cognition. *Learning and Individual Differences, 1*, 7–35.
- O'Boyle, M., Vaughan, D., Cunnington, R., Puce, A., Syngeniotis, A., & Egan, G. (2002). 3-Dimensional rotation in mathematically gifted adolescents: An fMRI investigation. *NeuroImage, 16*, S673.
- Oldfield, R. C. (1973). The assessment and analysis of handedness: The Edinburgh Inventory. *Neuropsychologia, 9*, 97–113.
- Robertson, L. C., Lamb, M. R., & Zaidel, E. (1993). Interhemispheric relations in processing hierarchical patterns: Evidence from normal and commissurotomy subjects. *Neuropsychology, 7*, 325–342.
- Schneider, W. (1988). Micro Experimental Laboratory [Computer software]. Pittsburgh, PA: Psychology Software Tools.
- Shepard, R. N., & Metzler, J. (1971, February 19). Mental rotation of three-dimensional objects. *Science, 171*, 701–703.
- Stanley, J. C., & Benbow, C. P. (1983). SMPY's first decade: Ten years of posing problems and solving them. *Journal of Special Education, 17*, 11–25.
- Van Kleek, M. (1989). Hemispheric differences in global versus local processing of hierarchical visual stimuli by normal subjects: New data and a meta-analysis of previous studies. *Neuropsychologia, 28*, 1165–1178.
- Weissman, D. H., & Banich, M. T. (2000). The cerebral hemispheres cooperate to perform complex but not simple tasks. *Neuropsychology, 14*, 41–59.
- Winner, E. (2000). The origins and ends of giftedness. *American Psychologist, 55*, 159–169.
- Witelson, S. F. (1985, August 16). The brain connection: The corpus callosum is larger in left-handers. *Science, 229*, 665–668.
- Zaidel, E. (1995). Interhemispheric transfer in the split brain: Long-term status following complete cerebral commissurotomy. In R. J. Davidson & K. Hugdahl (Eds.), *Brain asymmetry* (pp. 491–532). Cambridge, MA: MIT Press.

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