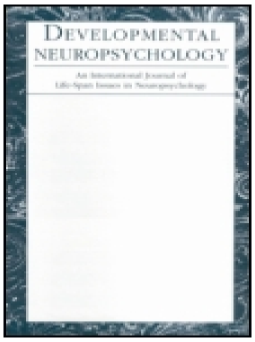

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Richard J. Haier & Camilla Persson Benbow

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Sex Differences and Lateralization in Temporal Lobe Glucose Metabolism During Mathematical Reasoning

Richard J. Haier
Departments of Pediatrics and Neurology
University of California, Irvine

Camilla Persson Benbow
Department of Psychology
Iowa State University

Positron Emission Tomography with [^{18}F]deoxyglucose was used to compare brain activation in men and women while they performed mathematical reasoning. Right greater than left-hemisphere activation was predicted, especially in temporal lobes. Forty-four participants were selected and matched for high or average Scholastic Aptitude Test–Math scores. There were no sex differences in cortical glucose metabolic rate (GMR). However, GMR in temporal lobe regions was positively correlated with math reasoning score in men but not in women. The temporal lobes, bilaterally, are implicated in math reasoning ability for men; no specific cortical areas were related to math reasoning performance in women.

Sex differences in cognitive abilities and achievement have been reported for several decades (Halpern, 1992; Maccoby & Jacklin, 1974). Differences are especially marked for mathematical reasoning ability and spatial ability, and both favor men. Verbal and language ability differences favor women.

Functional neuroimaging techniques have the potential to establish whether any sex differences in cognitive abilities are related to brain differences. For example, Shaywitz et al. (1995) used functional magnetic resonance imaging (MRI) to study

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Requests for reprints should be sent to Richard J. Haier, Departments of Pediatrics and Neurology, Irvine Hall, Room 100, University of California, Irvine, CA 92717–4275. E-mail: RJHAIER@UCI.EDU

sex differences in brain organization for language functions. They found that phonological processing in men activated left inferior frontal gyrus areas. In women, however, activation in both left and right hemisphere was noted. Such clear sex differences in brain function have been less apparent in studies using Positron Emission Tomography (PET) to determine blood flow or glucose metabolic rate (GMR), both of which assess neuronal activity. However, Gur et al. (1995) reported higher GMR in right and left temporal lobes in men. Most PET studies of sex differences report few GMR differences whether the studies use a cognitive task (Andreason, Zametkin, Guo, Baldwin, & Cohen, 1994; Mansour, Haier, & Buchsbaum, in press) or a rest condition (Azari et al., 1992).

Some evidence suggests that mathematically talented men appear to possess enhanced right-hemispheric functioning, whereas mathematically talented women do not. This is reported by O'Boyle, Benbow, and Alexander (1995) using electroencephalogram recording during a word task and a spatial task. Among high-ability men, during the spatial task, the right temporal lobe was especially active, whereas the left temporal lobe was inhibited. This inhibition may have allowed the right hemisphere to play the predominant information-processing role. Interestingly, this left inhibition–right activation of the temporal lobes was not found for high-ability women or in the average-ability men or women. This suggested that a characteristic of the male gifted brain is the ability to selectively inhibit–activate relevant cortical regions necessary for specialized processing. The frontal lobes were active for all groups in the spatial task, but only the gifted showed enhanced frontal lobe activation in the word task.

Are the brains of high-math-ability men and women organized differently? The purpose of this study was to test the right-hemisphere cortex hypothesis and to explore other potential differences in brain function in frontal and temporal lobe using PET in men and women of high and average mathematical reasoning ability.

METHOD

Participants

Using campus-wide advertisements, we recruited 44 male and female volunteers with Scholastic Aptitude Test–Math (SAT–M) scores either over 700 (high-ability group, 95th percentile of college-bound seniors) or between 410 and 540 (average-ability group, 30th to 68th percentiles). SAT scores were verified with official records. All participants were right-handed, in good physical health, and had no history of psychiatric illness or head injury. The ages and SAT scores for male and female participants in each group (high and average math ability) are shown in Table 1.

TABLE 1
Age and Scholastic Aptitude Test (SAT) Scores for Men and Women in High and Average SAT-M Groups

Group	*n*	*Mean Age*	*SD*	*Mean SAT-M*	*SD*	*Mean SAT-V*	*SD*
High/Men	11	20.3	1.5	733	30	563	80
Average/Men	11	20.1	2.4	470	39	404	76
High/Women	11	19.5	1.5	727	25	555	103
Average/Women	11	19.5	1.5	471	46	435	110

Note. SAT-M = SAT-Math; SAT-V = SAT-Verbal. High groups had SAT-M scores greater than 700; average groups had SAT-M scores between 410–540.

Procedures

Each participant completed one PET scan using [^{18}F]deoxyglucose (FDG) as the uptake marker of regional cerebral GMR. During the 32 min FDG-uptake period, participants performed the same set of 23 SAT–M items (Form DSA016HM, Section 2) reported to have minimal sex bias (Benbow & Wolins, in press). During the uptake period, the mean number of SAT–M items correct for the high/male group was 22.1 (*SD* = 1.4); for high/female group, 21.1 (*SD* = 2.4); for average/male group, 12.8 (*SD* = 2.4); for average/female group, 13.4 (*SD* = 3.7). In the high/male group, the range of number correct was 20–24 and had no overlap with the range of 9–17 in the average/male group. In the high/female group, the range of number correct was 17–24, with 9–20 in the average/female group. Two women in the high group were in the average range (with scores of 17 and 18), and 1 woman in the average group scored 20. *T* tests showed that the groups selected for high and average SAT–M scores, in fact, had significantly different scores during the uptake task (i.e. number correct) for both the men and women. For all 22 men, the mean math score was 17.5 (*SD* = 5.1, range = 9–24); and the mean score for 22 women was 17.2 (*SD* = 5.0, range = 9–24).

Scanning took place immediately after the uptake period SAT–M testing with a CTI NeuroEcat Scanner (FWHM resolution was 7.8 mm in plane and 10.9 mm in the z-dimension). The scanning always must occur after the brain has been labeled with the FDG for the 32 min uptake period during which the participant works the math items. The pattern of glucose metabolism during this time is fixed by the FDG method so that the subsequent scanning shows the accumulated glucose use during the task.

PET Analyses

GMR was measured in micromoles glucose per 100 g brain tissue per minute, following Sokoloff et al. (1977). Because whole brain GMR varies considerably from person to person, we divided GMR in each region-of-interest by whole-brain GMR. This resulted in relative GMR determinations for each area that are corrected for whole-brain GMR variations. Each cortical region-of-interest was defined by a standard stereotactic method (Buchsbaum et al., 1989; Haier et al., 1992) with each lobe divided into four segments across slices (Figure 1). This stereotactic template method is similar to other methods based on a standard brain outline to which each individual scan is fit; no clear advantage of any one method has been reported. All these methods generate a large number of statistical comparisons in sample sizes relatively small for multivariate statistical corrections. Here, however, we present only 16 comparisons per hemisphere rather than thousands of pixel-to-pixel comparisons. All comparisons are directed at a specific hypothesis.

Data Analyses

To examine whether right-hemisphere cortical function is related to mathematical reasoning in men and women, we used four approaches. First, we computed a repeated-measures analysis of variance (ANOVA) on GMR and relative GMR. This was designed as a Group (High vs. Average SAT–M score) × Sex (Male vs.

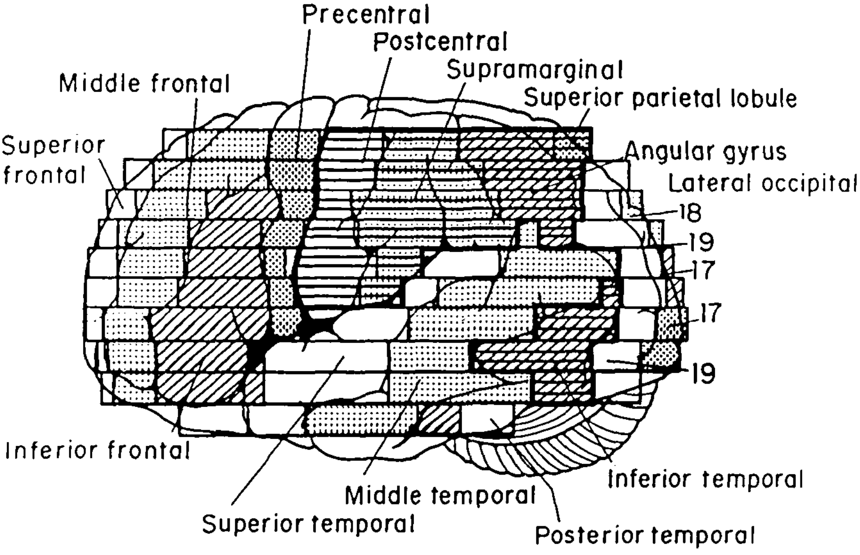

FIGURE 1 This right lateral view shows each lobe divided into four segments. Segments often are defined across multiple Positron Emission Tomography slices, as shown. Each segment is defined separately for right and left hemispheres.

Female) × Hemisphere (Right vs. Left) × Lobe (Frontal, Parietal, Temporal, Occipital) × Segment (four per lobe; see Figure 1) ANOVA using Huynh-Feldt degrees of freedom (BMDP4V, using the structure option to ensure nesting of segments within lobes and lobes within hemispheres). Second, we correlated GMR and relative GMR in each cortical segment with the math score attained during the FDG uptake period, left and right hemispheres separately, in the 22 men and the 22 women. If mathematical reasoning ability in either men or women is a function of the right cortex, there should be more correlations in the right hemisphere than in the left. Third, we correlated right minus left hemisphere GMR and relative GMR values in each cortical segment with the math score attained during the FDG uptake period; this was done separately for men ($n = 22$) and women ($n = 22$). Positive correlations would indicate that greater asymmetry favoring the right-hemisphere segment was related to better math score. Fourth, we correlated GMR and relative GMR in each right-hemisphere cortical segment with the corresponding segment in the left hemisphere. A failure to find cross-correlations may indicate greater laterality in either men or women as they perform mathematical reasoning.

The ANOVA approach used the high and average SAT–M selection criteria to define discreet groups based on ability, whereas the correlational approaches combined high- and average-ability groups and used the range of math scores attained during the FDG uptake as a continuous variable. For the correlation analyses, two-tailed tests, $p < .05$, are used.

RESULTS

The ANOVA (Group × Sex × Hemisphere × Lobe × Segment) on all 44 participants showed no significant main effects or interactions for GMR or relative GMR. Table 2 shows cortical GMR in each hemisphere and lobe for the four groups; Figure 2 shows group-average PET images for a single slice.

Each Positron Emission Tomography image in Figure 2 is an average composite of glucose metabolic rate (GMR) for one axial slice level (44% of head height) based on the 11 participants in each group. The scale shows micromoles glucose/100 g brain tissue/minute. Note higher GMR in men who have high Scholastic Aptitude Test–Math scores than in the other three groups. Arrows indicate temporal lobe areas.

Table 3 shows the cortical segments (see Figure 1) where GMR was significantly correlated with math score in men ($n = 22$) and women ($n = 22$), separately for right and left hemispheres. For GMR in the men, three of the four temporal lobe segments (middle, inferior, posterior) are significant bilaterally ($rs > .42$, two-tailed test) and the fourth segment (superior) just missed a $p < .05$ level ($r = .40$ and $.39$, left and right hemispheres, respectively). No other correlations between GMR or relative GMR and math score were significant, but we have appended all the GMR

TABLE 2
Mean Glucose Metabolic Rate (GMR) in Cortical Lobes for Each Hemisphere for Each Group

	High/Men				*High/Women*				*Average/Men*				*Average/Women*			
	Left		*Right*		*Left*		*Right*		*Left*		*Right*		*Left*		*Right*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Frontal	38	8	38	8	35	10	35	10	32	5	32	5	32	5	32	5
Parietal	37	9	38	9	35	12	35	13	32	5	32	5	32	6	33	6
Temporal	29	5	31	5	27	6	29	7	25	4	26	4	26	5	27	4
Occipital	36	8	37	9	35	11	36	11	32	5	33	5	34	6	34	7
Whole cortex	35	8	36	8	33	10	34	11	30	6	31	5	31	6	31	6

Note. GMR is given as micromoles glucose per 100 g brain tissue per minute, rounded to the nearest whole number. Each lobe has four segments; see Figure 1.

TABLE 3
Correlations Between GMR and Math Score in Left and Right Temporal Lobe Segments For Men and Women

	Left Hemisphere		*Right Hemisphere*	
Segment	*Men*[a] *(r)*	*Women*[b] *(r)*	*Men*[a] *(r)*	*Women*[b] *(r)*
Superior temporal	.40	.09	.39	.16
Middle temporal	.44*	.10	.42*	.15
Inferior temporal	.46*	.13	.46*	.17
Posterior temporal	.45*	.16	.55**	.04

[a]$n = 22$. [b]$n = 22$.
*$p < .05$, two-tailed test. **$p < .01$, two-tailed test.

correlations from frontal, parietal, and occipital segments. None of the significant correlations in the temporal lobes were artifacts caused by outliers, as illustrated in the representative scatterplot shown in Figure 3. In the women, GMR–math score correlations were not significant in any cortical segment (none of the temporal segment *r*s exceeded .17); two occipital segments showed negative correlations with relative GMR (Area 19 on the left and Area 17 on the right). Ranges of math scores and GMR were nearly identical for male and female participants.

When right-hemisphere minus left-hemisphere GMR and relative GMR in each cortical segment was correlated with math score in our third analysis, no correlations were statistically significant for either men or women, indicating no relation between right and left GMR asymmetry and performance.

Our fourth analysis was based on correlations between right and left hemisphere in each of the 16 cortical segments. For both GMR and relative GMR, all 16 segments were highly correlated between hemispheres in both the male and female participants (all but two correlations were greater than .92, $p < .001$; the other two

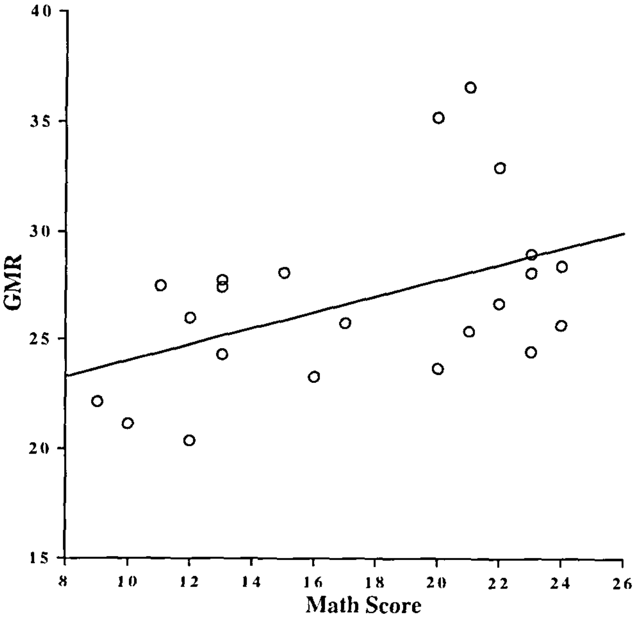

FIGURE 3 This scatterplot shows the glucose metabolic rate math score correlation ($r = .46$, $p < .05$) in the men for the left inferior temporal lobe segment (see Figure 1).

correlations were greater than .77, $p < .001$). The close coupling of right- and left-hemisphere GMR segment by segment is consistent with the lack of any hemisphere effect.

DISCUSSION

None of the analyses were consistent with right-hemisphere greater than left-hemisphere involvement in mathematical reasoning for either men or women. This is consistent with other PET studies in which minimal hemisphere differences between men and women have been found. Only one functional MRI study indicated hemisphere sex differences in language ability (Shaywitz et al., 1995); no functional MRI studies of spatial or mathematical ability are yet reported.

In men, there were positive correlations between math score and GMR in temporal lobe segments in both right and left hemispheres. This suggests specific cortical involvement in mathematical reasoning for men, partially consistent with O'Boyle et al. (1995). Because, however, we have no comparison task data, we can not conclude that these temporal lobe correlations are unique to mathematical and not verbal reasoning or other cognitive abilities. It should also be noted that several frontal lobe and a few parietal lobe segments showed correlations between GMR and math score that approached statistical significance (see Appendix).

In the women, no cortical segment GMR was correlated with math score. Although this may suggest that the temporal lobe is not as important in women as it appears to be in men, a cortical basis for mathematical reasoning in women is not apparent. If women were more inclined to use a verbal strategy for solving math problems, for example, GMR in cortical language areas may have been correlated with math score. There were no such correlations.

Given the selection for superior mathematical reasoning ability in this study, it is surprising that there was no stronger group effect, $F(1, 40) = 3.08, p = .087$. Yet, Table 2 does reveal that GMR is higher overall in the high SAT–M men than in the other three groups. It is interesting that men who have high SAT–M scores are overrepresented in the population, and women who have high SAT–M scores are found in about the numbers predicted by the normal curve (Benbow, 1988). We might speculate that the men who have high SAT–M scores have a different way of mathematical reasoning from everyone else (Benbow & Lubinski, 1993), although this is not strongly apparent in our data.

Based on earlier PET studies of intelligence (Haier, 1993; Haier et al., 1988), learning (Haier, Siegel, MacLachlan, Soderling, Lottenberg, & Buchsbaum, 1992; Haier, Siegel, Tang, Abel, & Buchsbaum, 1992), and mental retardation (Haier et al., 1995), one might have anticipated an inverse relation between GMR and math scores, especially in temporal lobe. Recently, however, we reported (Larson, Haier, LaCasse, & Hazen, in press) that adjusting the mental effort required for task performance shows high GMR in high-IQ men during a difficult task compared to an easy version of the same task (i.e., digit span backward). Thus, in men, the direction of GMR–cognitive performance correlations, as well as their regional distribution, appears to vary according to specific task choice, task difficulty, and subject ability level. A similar set of studies have yet to be done in women.

CONCLUSION

We found no evidence of right greater than left temporal lobe GMR in men than women at either high or average math ability level. A major sex difference was noted in temporal lobes. In men, high temporal lobe GMR was related to better SAT–M performance, bilaterally, but this was not true for women. No other cortical areas were related to SAT–M performance in the women. Further exploratory analyses in subcortical brain areas may find other GMR sex differences that underlie mathematical reasoning.

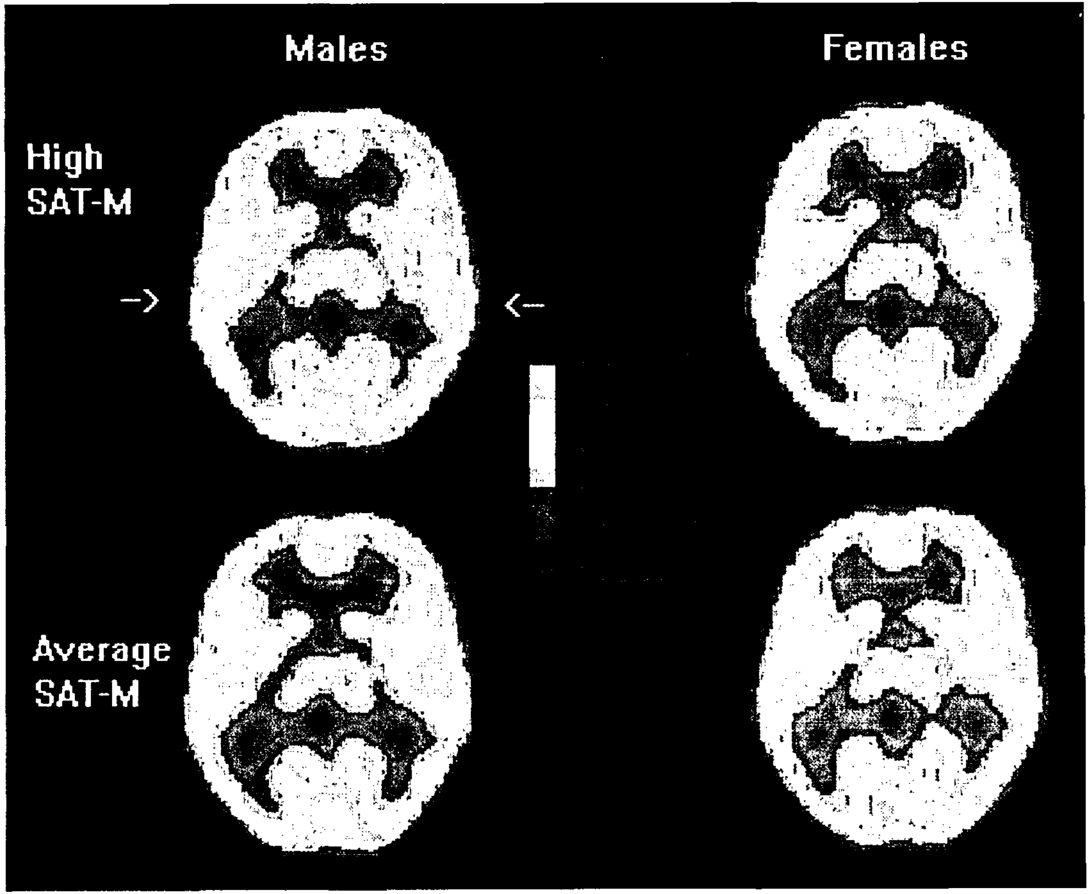

FIGURE 2 Group average PET images for single slice.

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APPENDIX

Correlations Between Glucose Metabolic Rate in Left and Right Hemisphere Segments of the Frontal, Parietal, and Occipital Lobes for Men and Women

	Left Hemisphere		*Right Hemisphere*	
Segment	*Men*[a] *(r)*	*Women*[b] *(r)*	*Men (r)*	*Women (r)*
Superior frontal	.40	.12	.40	.19
Middle frontal	.41	.21	.33	.16
Inferior frontal	.39	.14	.40	.15
Precentral frontal	.35	.13	.35	.13
Postcentral parietal	.40	.11	.41	.06
Supramarginal parietal	.35	.12	.33	.12
Superior parietal	.29	.07	.27	.15
Angular gyrus	.23	.09	.26	.10
Occipital 19	.28	.04	.34	.07
Occipital 17	.19	.04	.26	−.06
Occipital inferior 17	.21	.17	.28	.15
Occipital 18	.26	.05	.28	.12

Note. See Figure 1 for segments of lobes. No correlations are significant ($r > .423$ for $p < .05$, two-tailed).

[a]$n = 22$. [b]$n = 22$.