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Mathematically Gifted Children: Developmental Brain Characteristics and Their Prognosis for Well-Being

Michael W. O'Boyle

Research in cognitive neuroscience suggests that the brains of mathematically gifted children are quantitatively and qualitatively different from those of average math ability. Math-gifted children exhibit signs of enhanced right-hemisphere development, and when engaged in the thinking process, tend to rely on mental imagery. They further manifest heightened interhemispheric exchange of information between the left and right sides of the brain, reflecting an unusual degree of neural connectivity. Consequently, educators should develop instructional techniques that capitalize on the special learning styles of math-gifted children. Such methods may include multimodal lecture presentations and other classroom activities that highlight the use of visual images. Creating specialized outreach programs in math/science to provide supplemental learning experiences not often supplied by understaffed and underresourced school systems may prove particularly valuable to the development of math-gifted children. Until such measures are commonplace, society's best young thinkers risk underachievement. Policy changes are needed to address the needs of math-gifted children and to enhance their developmental well-being.

A selective review of the cognitive neuroscience literature (Butterworth, 1999; Dehaene, 1997) yields support for a neurobiological foundation to exceptional mathematical ability. One proposed brain characteristic of math giftedness is the enhanced development of the right cerebral hemisphere (RH) and an unusual reliance on its specialized visuospatial processing capacities (Geschwind & Galaburda, 1984; O'Boyle, Benbow, & Alexander, 1995). Another is a special form of brain bilateralism (O'Boyle et al., 2005), involving heightened connectivity and integrative exchange of information between the left and right cerebral hemispheres (O'Boyle & Hellige, 1989; Singh & O'Boyle, 2004).

Evidence from brain-damaged patients reveals that deficits in mathematics are apt to follow injury to either cerebral hemisphere, but the nature of the impairment will differ depending upon the location (and sometimes the etiology) of the cerebral insult. For example, left hemisphere (LH) damage may result in difficulties with reading or writing numbers and the performance of basic arithmetic operations (e.g., acalculia or dyscalculia), while damage to the RH tends to disrupt spatial functions (e.g., visual confusion of mathematical signs, omitting numbers, and difficulties in preserving decimal places), as well as impairing higher order mathematical reasoning capacity (Benbow, 1988; Dehaene & Cohen, 1997; Dehaene, Dehaene-Lambertz & Cohen, 1998). When viewed from this perspective, note that the emphasis is placed on the manner and degree to which both hemispheres of the brain interact with each other as processing partners, the latter being crucial to the mastery of a complex cognitive process like mathematics.

Data derived from several studies support an important relationship between the specialized visuospatial capacities of the RH and mathematical ability. For example, using positron emission tomography (PET), Haier and Benbow (1995) showed increased glucose metabolism in the right temporal lobe during a mathematical reasoning test of high (but not gifted) ability students. And Presenti et al. (2001), also using PET, found calculation in an adult mathematical prodigy to be partly mediated by the right prefrontal and right medial temporal cortex. In other neuroimaging studies, the interactive contributions of both hemispheres to mathematical reasoning have been demonstrated using the electroencephalogram (EEG) and event-related potential (ERP), with the relative importance of each hemisphere to mathematics being problem type and strategy dependent (Burbaud et al., 1999; Kazui, Kitagaki, & Mori, 2000). Interestingly, a recent postmortem examination of the brain of Albert Einstein (Witelson, Kigar, & Harvey, 1999), certainly one of the world's premiere mathematical thinkers,

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Address correspondence to Dr. Michael W. O'Boyle, Department of Human Development and Family Studies, Texas Tech University, Box 41230, Lubbock, TX 79409. E-mail: michael.oboyle@ttu.edu

has revealed enhanced development of the inferior parietal lobes, which may reflect the importance of visual imagery to high-level mathematical thinking.

Over the years, O'Boyle and colleagues have conducted considerable research into the morphological and functional characteristics of the mathematically gifted brain in adolescents and how it differs both qualitatively and quantitatively from those of average-math-ability youths (e.g., O'Boyle, 2000; O'Boyle, Alexander, & Benbow, 1991; O'Boyle & Benbow, 1990; O'Boyle, et al., 1995; O'Boyle, et al., 2005; O'Boyle & Gill, 1998; O'Boyle, Gill, Benbow, & Alexander, 1994; Singh & O'Boyle, 2004). In these studies, a variety of experimental methods have been used to demonstrate that enhanced development of the RH and an unusual reliance upon it when processing information are unique characteristics of the math-gifted brain. Note that in these studies, math-gifted children are operationally defined as 10- to 15-year-olds who have scored at the 99th percentile when taking the SAT-Math exam (Scholastic Aptitude Test, United States) or the SCAT-Numerical Reasoning test (School College Abilities Test, Melbourne, Australia).

Regarding the functional organization of the math-gifted brain, O'Boyle and Benbow (1990, exp. 1) used a dichotic listening paradigm to demonstrate that children of average math ability show the prototypic right ear/LH advantage when recognizing linguistic stimuli (e.g., syllables), whereas, contrastingly, the mathematically gifted are equally able at recognizing verbal stimuli with either ear. The latter finding suggests enhanced involvement of the RH during information processing, even when analyzing stimuli that are primarily linguistic/verbal in nature.

Likewise, O'Boyle et al. (1994) had mathematically gifted and average-ability youths perform a concurrent finger-tapping task, one that involves tapping a key pad with the index finger of each hand (one hand at a time) while simultaneously reading a paragraph out loud. Average-ability participants showed a significant reduction in tapping rate (relative to baseline) for the right hand/LH when reading, whereas their left-hand tapping rate was virtually unaffected (i.e., the same rate as baseline). This pattern is thought to reflect a division of LH (but not RH) resources between the linguistic processes necessary for reading the paragraph aloud and for those motor processes required for control of the right finger when tapping. For the math-gifted, however, significant reductions in the tapping rate of both hands relative to baseline were observed, as if both hemispheres were equally engaged (and equally able) at performing this linguistic/verbal task. This pattern dovetails with the aforementioned dichotic listening results showing bilateral processing of syllables, and each result supports the notion of enhanced development of the RH, along with an unusual reliance upon a special form of bilateralism when processing information, even for the analysis of linguistic (i.e., predominantly LH specialized) stimuli.

Further evidence for enhanced RH development and heightened reliance on its specialized visuospatial capacities in the math-gifted comes from an investigation conducted by O'Boyle and Benbow (1990; exp 2). In this study, the free-vision chimeric face task (CFT) developed by Levy and colleagues (Levy, Heller, Banich, & Burton, 1983) was employed. When performing, the CFT participants viewed pairs of chimeric faces (i.e., half smile/half neutral face composites compared to their mirror image), and were required to judge which of the two appears to be the "happier" (see Figure 1).

In light 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 (1990) predicted that both the math-gifted and the average-math-ability participants would demonstrate an RH bias in the performance of this task (i.e., selecting a greater percentage of left side smile/right side neutral face composites as happier), but that the math-gifted would show an even stronger bias due to their hypothesized enhanced RH functioning. Their results revealed that the math-gifted did indeed choose the left side smile/right side neutral composites significantly more often than average-ability participants, a pattern suggestive of greater involvement and processing reliance on the RH. Interestingly, O'Boyle and Benbow correlated the degree of RH bias as indexed by their CFT score (i.e., a laterality quotient computed as $LQ = (R-L)/N$) with their SAT score. This correlation was found to be significant and indicated that the greater the RH engagement (bias) when performing the CFT, the higher the SAT score. Such findings were interpreted as additional support for the notion of enhanced RH functioning as a brain characteristic of the math-gifted.

In a follow-up to the aforementioned study, O'Boyle et al. (1991) used the EEG to determine whether the pattern of hemispheric activation found in the math-gifted during performance of the CFT differed from that of average-math-ability children. Their results revealed that at baseline (i.e., looking at a blank slide), the math-gifted were primarily LH active. When engaged in the CFT, however, they shifted to focalized activation of the right frontal and temporal/parietal areas, engaging the very regions thought to be involved in judgments concerning the emotional content of a face (Banich, 1997). In contrast, average-math-ability children were as likely to shift right as left, or anterior as posterior during CFT performance. This ambiguous pattern of activation was thought to reflect a less developed (or more immature) state of functional cerebral organization in the average-ability children. When taken in composite, these data suggest that the math-gifted were better able to access and coordinate the cortical resources of the RH during information processing, and that their brain is characterized by a unique capacity to switch activation from one region to another (perhaps via the corpus callosum), as evidenced by their ability to shift from

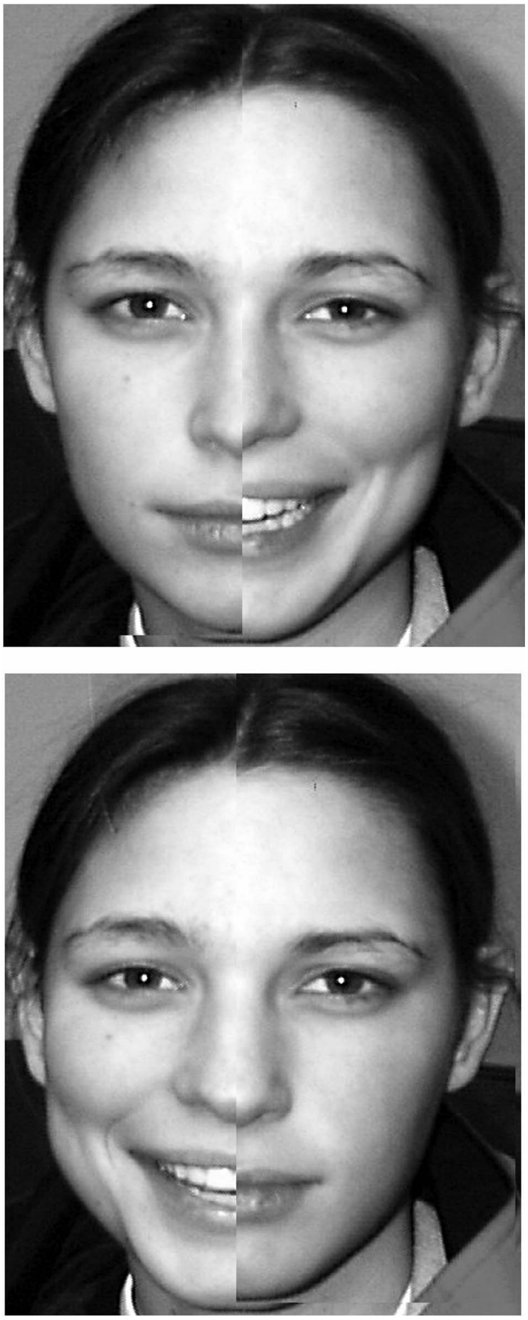

FIGURE 1 A sample chimeric face trial.

LH activation at baseline to localized activation of the RH during performance of the CFT.

In a study designed to further investigate the highly coordinated and orchestrated ability of the math-gifted brain to exchange information between the hemispheres, Singh and O’Boyle (2004) found average-math-ability children to be faster and more accurate in making same/different judgments of hierarchical letter pairs when they were presented unilaterally (i.e., both letters of the pair presented to the same hemisphere) as compared to bilaterally (i.e., when one letter of the pair is presented to each hemisphere simultaneously, thus requiring interhemispheric exchange of information to successfully complete the task). In contrast, the mathematically gifted were faster and equally accurate on bilateral trials as compared to unilateral trials, suggestive of a brain organization that is uniquely predisposed toward a high degree of interhemispheric interaction and is characterized by rapid and accurate information exchange between the hemispheres without the usual processing penalties or costs.

This brief and somewhat selective review of the empirical evidence pinpoints enhanced RH functioning and heightened interhemispheric interaction between the cerebral hemispheres as two processing characteristics that underlie exceptional mathematical ability, at least in children/adolescents. However, the functional organization of the math-gifted brain studied from a more anatomical perspective has only recently begun in earnest, with new research employing advanced brain-imaging techniques that are particularly useful in revealing the underlying neurobiological substrate of mathematically giftedness.

One recent study of this sort, investigating potential differences in the functional brain organization of mathematically gifted children, was conducted by O’Boyle et al. (2005). Functional magnetic imaging (fMRI) was employed to monitor brain activation during performance of a mental rotation task. Note that mental rotation is a visuospatial task that is oftentimes (though not uniformly) reported to correlate with mathematical ability (i.e., the better at mental rotation, the higher the math ability). In this study, 6 math-gifted boys (mean age = 14.3 years) and 6 matched control children performed 3-D mental rotation problems while in the fMRI scanning environment. On each trial, participants were required to press one of four fiber optic buttons to indicate which of the four test objects was identical to the target object when rotated in space (see Figure 2).

As can be seen in the accompanying headplots, for average-math-ability children, predominant activations were

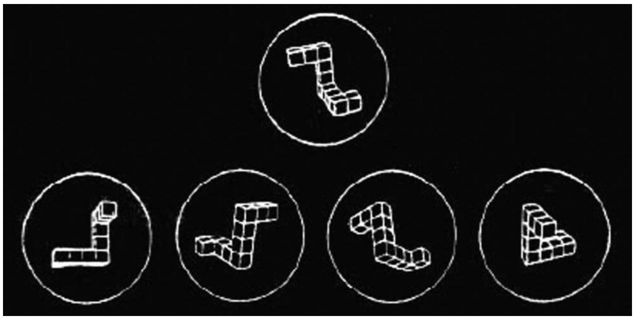

FIGURE 2 A sample mental rotation problem.

Note. From “Mathematically Gifted Male Adolescents Activate a Unique Brain Network During Mental Rotation,” by M. W. O’Boyle et al., 2005, *Cognitive Brain Research, 25,* pp. 583–587. Copyright 2005 by Elsevier. Reprinted with permission from *Cognitive Brain Research.*

found in the right frontal region (relating to spatial working memory) and the right parietal lobe (relating to the maintenance and manipulation of mental, perhaps, visual images); there was only slight evidence of any LH activation. For the math-gifted children, however, the amount of brain activation obtained was several times greater than that of average-math-ability children, and the overall pattern of activity was distributed quite differently. Specifically, there was bilateral activation of the right and left frontal regions, along with significant bilateral activation of the premotor, parietal, and superior occipital regions. Of particular note was the heightened activation of both the right and left anterior cingulate in the math-gifted children as compared to those of average math ability (see Figure 3).

These results indicate that math-gifted children recruit unique brain regions not typically engaged by those of average math ability, particularly the bilateral activation of prefrontal cortex, the parietal lobes, and the anterior cingulate. Note that the latter regions are thought to form a neural circuit known to mediate spatial attention and working memory as well as contributing to the fine-tuning of executive functions (Mesulam, 2000). They may also play an important role in deductive reasoning and, to a lesser extent, the development of cognitive expertise (Knauff, Mulack, Kassubek, Salih, & Greenlee, 2002).

By way of summary, both the behavioral and neuroimaging findings reported here suggest three general characteristics that best describe the operating properties of the mathematically gifted brain: (a) enhanced development of the RH, resulting in a unique form of functional bilateralism, with specialized contributions from both sides of the brain combining to drive cognition and behavior; (b) enhanced interhemispheric communication and cooperation (perhaps via the corpus callosum or increased grey/white matter ratio, or glia/neuron ratio), which assist in coordinating and integrating information between the cerebral hemispheres; and (c) heightened brain activation, approximating (or exceeding) that of an adult brain even though they are still adolescents, which is suggestive of enhanced processing power and may reflect highly developed attentional and executive functions that serve to fine-tune their unique form of cerebral organization.

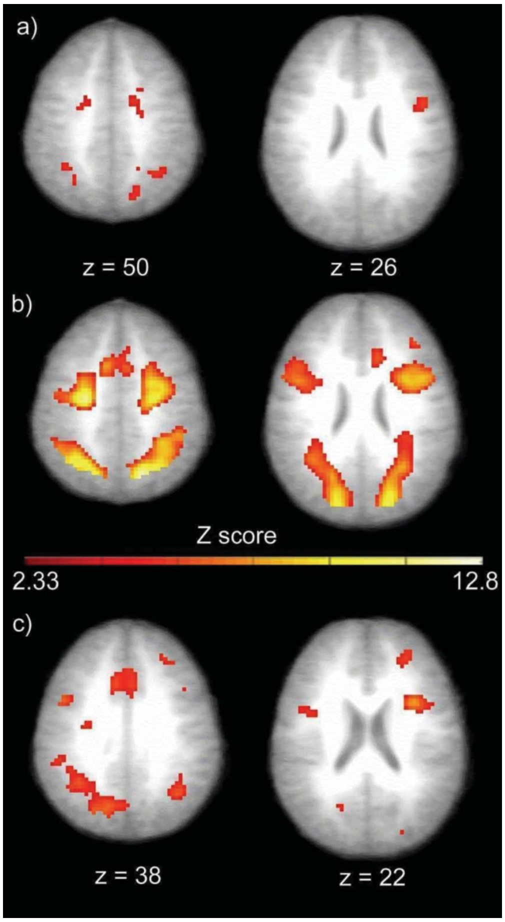

FIGURE 3 Headplots of (a) average math ability children, (b) math gifted children, and (c) areas uniquely activated in the math gifted children compared to those of average math ability. Reprinted with permission from *Cognitive Brain Research*.

Educational Implications

Given that mathematically gifted children possess a unique functional brain organization, several educational implications may follow. The first of these involves the use of specialized classroom techniques designed for gifted-level math instruction. For example, in light of their tendency for bilateral engagement of brain regions that are highly involved in spatial and visual imagery, it seems logical for teachers in the classroom to provide and rely upon multimodal learning methods when instructing math-gifted children. Multimodal methods that highlight the interaction and differential processing responsibilities of various brain regions, as well as the use of imagery-based mental representations, would seem a natural fit when attempting to map instructional techniques to the specialized learning styles relied upon by math-gifted children.

Moreover, it should be mentioned that flexible methods of assessment must also be implemented as part of the pedagogical process, given that math-gifted children are not likely to use the same types of cognitive strategies as more average-ability children. This may place them at a disadvantage when it comes to demonstrating their true ability on traditionally scored math exams and other standardized evaluative measures. For example, the frequent request by teachers to "show all your work" is unlikely to be adhered to or met with much enthusiasm by the math-gifted child, who often fails to see what "work" is actually required to solve such "simple" and "uninteresting" problems. As an aside, sometimes teachers actually (and usually mistakenly) assume that because no work was shown, the answer must have been copied from another student. After all, how could they know the answer to the problem without providing insight into the processes that led them to the solution?

An additional difficulty experienced by the math-gifted child is that they are often “bored to tears” in their current classroom environment, a fact that contributes to at least two undesirable outcomes. The first of these is for math-gifted children to engage in disruptive classroom behaviors in an effort to relieve their boredom. They find the work unchallenging and therefore uninteresting and are thus prone to “acting out” in the classroom, a situation that disrupts learning not only for themselves but for all of the students around them. One way to minimize the probability of such disruptions is to supplement the learning experiences of math-gifted children with special outreach programs as they provide challenging (and thus interesting) educational opportunities beyond the scope of the typically underresourced classroom situations. For example, there are numerous university- and private industry–based “giftedness centers” that offer supplementary learning opportunities for math-gifted children, which serve to bridge the gap in their learning experiences (e.g., providing advanced classes in gene splicing, the study of fractals, the mathematics of the solar system, etc.).

A second undesirable outcome is the phenomenon of dummying down. The latter involves math-gifted children intentionally scoring below their actual potential on math exams and other evaluative measures, just to fit in better with their less talented classmates who are sometimes their best friends. Gifted children are very much aware of and sensitive to the fact that they are different, often denying that there is anything special about their abilities. They actively seek to be just like everyone else and, to that end, are talented enough to employ what might be considered a behavioral calculus. Such mental calculations provide the math-gifted child with an internal estimate of the scores that their classmates are likely to attain and assists them in purposefully adjusting their own performance to be roughly at the same level. Simultaneously (and here is where the “calculus” comes into play), they are able to assess just how low their score can be without provoking a reprimand by their teacher or a reprisal from their parents. Obviously, the employment of a dummying down strategy, while socially understandable, results in significant academic underachievement and, potentially, a tremendous waste of mathematical talent.

CONCLUSIONS

There is now, and has always been, intense fascination with those who exhibit exceptional mathematical ability, particularly children who acquire their prodigious math skills seemingly in the absence of any formal training or instruction. Most of us know someone who has a proclivity for mathematics, and each of us shares an intrinsic curiosity about how the brain of a “budding Einstein” might work. Of particular importance for the well-being of the math-gifted is the capacity to identify these children at the earliest possible age and to subsequently learn more about how to foster and develop their special math abilities to their full potential. While the present findings from cognitive neuroscience are certainly provocative, our current understanding of the neurobiological bases of mathematical ability remains in its infancy. As such, there is a growing need for investigations into the underlying brain structures and neural circuitry that serve as the anatomical foundation of exceptional intelligence in general (Jung & Haier, 2007; Kalbfleisch,Van Meter, & Zeffiro, 2006) and gifted math ability in particular (O’Boyle et al., 2005). Findings from such studies will undoubtedly assist parents, teachers, and hopefully, legislators, in the planning and implementation of classroom practices and governmental policies that ensure optimal development of math skills, not only in the math-gifted, but in all children irrespective of their ability levels. Failing to do so severely compromises their potential and in turn impacts negatively on our own and society’s well-being.

AUTHOR NOTE

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AUTHOR BIO

Professor O'Boyle is a nationally and internationally recognized expert in the biological bases of intelligence, particularly mathematical giftedness. His research involves the use of a variety of experimental techniques, including functional magnetic resonance imaging (fMRI), to investigate how individual differences in cognition relate to underlying differences in the structure and neural circuitry of the human brain. E-mail:michael.oboyle@ttu.edu