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Michael W. O'Boyle, Camilla Persson Benbow & Joel E. Alexander

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Sex Differences, Hemispheric Laterality, and Associated Brain Activity in the Intellectually Gifted

Michael W. O'Boyle and Camilla Persson Benbow
Department of Psychology
Iowa State University

Joel E. Alexander
Department of Psychology
Western Oregon State College

Benbow (1986) proposed that enhanced development of the right cerebral hemisphere may be associated with extreme intellectual giftedness. Here we report on a series of studies conducted to evaluate the viability of this hypothesis, using several neuropsychological methods (e.g., dichotic listening, concurrent finger-tapping, chimeric face, and word processing). Also presented are new data from electroencephalographic recordings of brain activity taken from precocious and average-ability male and female adolescents while they performed two of the aforementioned tasks. These experiments provide convergent lines of evidence suggesting that enhanced right-hemisphere involvement during basic information processing, as well as superior coordination and allocation of cortical resources within and between the hemispheres, are unique characteristics of the gifted brain. The evidence is especially compelling for precocious male adolescents, as gifted female adolescents tend to exhibit a somewhat more bilateral and diffuse state of functional brain organization.

Systematic identification of the physiological correlates of intellectual precocity commenced more than 12 years ago. It began in earnest shortly after the first had been reported—biological sex (Benbow, 1988; Chen & Buckley, 1988; Lubinski

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Requests for reprints should be sent to Michael W. O'Boyle, Department of Psychology, W112 Lagomarcino Hall, Iowa State University, Ames, IA 50011–3180. E-mail: MWOBOYLE@IASTATE.EDU

& Benbow, 1992). Sex differences in exceptional mathematical reasoning ability were first documented in the 1980s with the provocative report that there were many more boys than girls who are exceptional in math (Benbow & Stanley, 1980, 1983). That is, the male distribution of high scores on the College Board Scholastic Aptitude Test–Mathematics (SAT–M; a test of mathematical reasoning ability), earned before age 13, was discovered to have a negative skew (Benbow, 1988). Because this is not the case for the female distribution, there is a resultant excess of boys at the high end (e.g., 13 boys for every 1 girl are in the top 1-in-10,000 ability range). In light of this finding, subsequent research has focused on the factors that might account for this disproportionality.

Although intuitively clear that both nature and nurture are contributors to the observed sex difference in mathematical giftedness, their relative degree of influence has yet to be determined. For example, socio-environmental explanations are wide ranging and include differential course-taking in school, social attitudes, parent and teacher support and encouragement, gender stereotyping, and even test-item bias (Benbow, 1988). However, the majority of these nurture explanations have received weak support at best (Benbow, 1988; Benbow & Stanley, 1980, 1983; Lubinski & Benbow, 1992), even when interventions designed to eclipse potential differences between male and female adolescents in their interests and values have been implemented (Halpern, 1992). Moreover, in a recent meta-analytic review, Lytton and Romney (1991) called into question the very notion of differential socialization of boys and girls by their parents. These findings, as well as others, led us to explore the possible physiological correlates of this sex difference in precocious mathematical ability. A biological approach seemed fruitful, as a genetic contribution to ability differences had already been firmly established (Benbow, 1986, 1988).

Our work began with a neuropsychological emphasis due primarily to the findings of Geschwind and Behan (1982). In essence, they provided a theoretical basis for several of our investigations. Specifically, they hypothesized that left-handers suffer more frequently from immune disorders, learning disabilities, and migraines as compared to right-handers. Their proposed explanation for this association involved prenatal exposure to testosterone, suggesting that if the developing fetus is exposed to high levels of testosterone or has an increased sensitivity to this hormone, at least two sequenced biological manifestations result: (a) testosterone affects the development of the thymus gland and, thereby, leads to increased susceptibility to immune disorders, such as allergies and autoimmune disease; and (b) testosterone enhances the development of the nondominant hemisphere (typically the right hemisphere [RH]), which may lead to an increased incidence of left-handedness. (For further details, see a recent special issue of *Brain and Cognition*, Volume 26, 1994, that is devoted to a discussion of this hypothesis.)

Given that different patterns of functional brain organization may also strongly influence individual differences in cognitive abilities (Hellige, 1990, 1993; O'Boyle & Hellige, 1989), it was appealing to take the Geschwind and Behan hypothesis a step further by applying it to the observed sex difference in mathematical precocity (Benbow & Benbow, 1987). In this regard, Gardner (1983) as well as Troup, Bradshaw, and Nettleton (1983) reported that mathematical reasoning ability (e.g., the ability to discern patterns but not necessarily computational skill) may be more directly under control of the RH as compared to the left hemisphere (LH). Moreover, Levy and Gur (1980) suggested that high levels of fetal sex hormones may promote the maturational rate and cognitive development of the RH more so than the LH. Thus, it seemed plausible that just as there are continuous and taxonic avenues from which mental retardation can be traced, the opposite extreme—intellectual giftedness—may also stem from systematic sources of individual variation in brain morphology, functional organization, or both.

Our initial investigation into this domain began, therefore, with a study of the incidence of left-handedness and allergies among extremely precocious (i.e., the top 1 in 10,000) and moderately gifted youth (Benbow, 1986; O'Boyle & Benbow, 1990b). Frequency of myopia was also investigated given its reported relation to cognitive ability (Ashton, 1983). In the Benbow (1986) study, it was found that intellectually precocious youth, compared to their parents, siblings, and a moderately gifted comparison group, exhibited more than double the frequency of left-handedness, allergies, and immune disorders, as well as myopia. As suggested by Geschwind and Behan (1982), these characteristics may be a reflection of enhanced RH development. Notably, this pattern was found in spite of the fact that precocious youth tend to be physically healthier than their normative peers (Lubinski & Humphreys, 1992). Other findings of interest include that precocious children tend to be first born, which may have hormonal implications (see Maccoby & Jacklin, 1974), and quite curiously, there is a propensity for them to be born during a specified period of the year (February through July, with a peak in June and a low in December).

The identification of these physiological correlates led to a controversial proposal originally advanced by Benbow (1986) that enhanced RH development may be associated with extreme intellectual precocity, especially in boys. This contention prompted further systematic study of the idea, with some consistent findings. In this article, we review a portion of this work, as well as present new data, in an effort to make the case that the functional organization of the gifted brain is qualitatively different than that of average-ability individuals. Moreover, we attempt to show that data from several converging sources strongly suggest that enhanced involvement of the RH during basic information processing, and the superior coordination of cortical resources between the two hemispheres during intellectual engagement, are particularly related to giftedness, especially in boys.

HEMISPHERIC LATERALIZATION AND GIFTEDNESS

It is now well documented that the LH and RH of the human brain are specialized for different types of information processing, and particularly lateralized may be the various subcomponents underlying higher order thinking processes (Hellige, 1990, 1993; O'Boyle, 1986; O'Boyle & Hellige, 1989). For instance, there is known to exist a unique link between the LH and most language-related functions. Support for this connection can be found in numerous studies of brain-damaged patients who exhibit language production, comprehension deficits, or both, that occur almost exclusively as a result of damage to anterior regions of the LH; equivalent damage to homologous locations in the RH seldom, if ever, produce such deficits. There is also consistent support for LH language mediation from studies conducted on neurologically normal individuals. For example, in dichotic listening experiments, syllables (Hellige & Wong, 1983), words (McGlone & Davidson, 1973), and sentences (Zurif, 1974) are all better recognized when presented to the right ear–LH than vice versa. Moreover, the degree of this lateral advantage is known to vary as a function of stimulus type, with consonant–vowel syllable identification being the most discriminative task (Obrzut, 1995; Obrzut, Boliek, & Obrzut, 1986). In addition, in visual half-field studies, when verbal stimuli are presented to the right visual-field, a similar LH processing advantage is obtained (Hellige, 1980; Levy & Reid, 1976; O'Boyle, 1985, Experiment 1; O'Boyle & Hellige, 1982).

In contrast, the RH is thought to bear primary responsibility for the mediation of fundamental aspects of visuospatial processing. Evidence from clinical populations has demonstrated that deficits in the perception of patterns, recognition of human faces, and the ability to localize objects in coordinate space all tend to follow insult or injury to primarily the RH (Hellige, 1990, 1993; O'Boyle, 1986; O'Boyle & Hellige, 1989). These findings are buttressed by experiments conducted on neurologically normal individuals in which dichotic listening for melodic patterns (King & Kimura, 1972), musical chords (Gordon, 1980), and various environmental sounds (e.g., clocks ticking, dogs barking, and so forth, as in Knox & Kimura, 1970) all produce higher recognition rates for left ear–RH as compared to right ear–LH presentations. In a similar vein, visual processing of random shapes (Hellige & Cox, 1976) and the identification of unfamiliar faces (Moscovitch, Scullion, & Christie, 1976) is typically faster and more accurate when such stimuli are presented to the left visual-field–RH.

Taken in composite, these findings suggest that the brain is a modular system, with the two cerebral hemispheres serving as specialized partners of a processing team, each contributing its own unique capacities to information processing. By way of speculation, it may be through this differential processing partnership that individual differences in cognitive abilities and talents emerge.

INDIVIDUAL DIFFERENCES IN LATERALITY

Whereas LH language–RH visuospatial lateralization may be the prototypical pattern of functional organization in the brain, there are individuals, and indeed groups of individuals, who systematically deviate from this processing arrangement (Bryden, 1990; O'Boyle & Hellige, 1989). The issue of primary importance here is whether the gifted brain is organized in a qualitatively (*not just* quantitatively) different fashion than that of average-ability individuals. Specifically, we believe that enhanced involvement of the RH, and the coordination of LH and RH processing resources during higher order thinking, are particularly related to intellectual giftedness and may serve as a physiological basis of precocity. In an effort to investigate these hypotheses, a series of experiments were undertaken to determine if the pattern of hemispheric organization, and thus the processing contributions of the LH and RH, are indeed different in those of extreme intellectual ability.

In all of our studies, we have used an operational definition of *giftedness.* The participants are young boys and girls between the ages of 11 and 13 who are part of the Iowa State University Office of Precollegiate Programs for Talented and Gifted. Precocious individuals have composite SAT scores that average 1100 (on a scale from 200 minimum to 1400 maximum), thus representing the top half of 1% in overall performance when adjusted for age. Matched control participants are of average ability and, by definition, unable to successfully negotiate the SAT at this age and level of intellectual development; when given the exam, their mean score is often about 200 (i.e., a floor effect). It is worth mentioning that many of the gifted participants attain their extreme level of ability by virtue of unusually high SAT–M scores. Their SAT–Verbal (SAT–V) scores, though better than average, are generally below their SAT–M scores. As briefly discussed later, this fact may have some interpretive significance.

All of the investigations that follow were designed to test if the pattern of functional organization characterizing the gifted brain is different from that of average-ability individuals. The techniques of investigation include dichotic listening for syllables, finger-tapping during a concurrent verbal memory load, and processing of words and chimeric faces with concomitant electroencephalographic (EEG) recordings. The intent was to derive support for our hypotheses from a variety of converging sources.

DICHOTIC LISTENING

One well-known technique for demonstrating patterns of hemispheric lateralization is the dichotic listening paradigm. In this procedure, two auditory stimuli are presented simultaneously—one to each ear (at equal volume and time duration)—and the task is to identify which two, from among several foils, were the ones presented. This technique reveals hemispheric dominance patterns because under conditions of simultaneous input, information from one ear projects solely to the contralateral hemisphere, thus enabling comparison of right ear–LH and left ear–RH performance in relative isolation (Kimura, 1961). As previously mentioned, when verbal materials like syllables or words are used as stimuli, participants are better at identifying those presented to the right ear–LH as compared to left ear–RH. This performance advantage is thought to reflect the specialized connection between the LH and the processing of language-related information. Linguistic inputs to the left ear–RH must be shuttled across the Corpus Collosum, resulting in less effective processing.

In one study (O'Boyle & Benbow, 1990a, Experiment 1), we had gifted and average-ability participants perform a dichotic listening for syllables task—one that had previously produced a robust right ear–LH performance advantage in average-ability, college-age participants (cf. Hellige & Wong, 1983). It was anticipated that average-ability adolescents would show the same prototypical LH advantage; however, for the gifted, the expected pattern was more difficult to predict. The reason for this was the fact that Benbow (1986) demonstrated that members of her precocious group tend to show several "soft" physiological signs of what might be considered enhanced RH development. As mentioned earlier, the gifted tend to be more left-handed than expected relative to the population at large and exhibit greater susceptibility to immune disorders. Each of these may be considered characteristics of enhanced RH development (Geschwind & Behan, 1982). The logic here is that if the RH of the gifted individual is indeed more developed (perhaps as a by-product of prenatal exposure to testosterone, a factor that may also account for the 13:1 ratio of boys to girls found in the gifted group), it may play a more prominent role in basic information processing. Thus, during dichotic listening, gifted participants may show only a small right ear–LH advantage; no asymmetry at all; or in the most extreme case, a left ear–RH advantage. Notably, the latter pattern would be directly opposite of that exhibited by most right-handed individuals.

In the O'Boyle and Benbow study, 47 gifted (33 boys, 14 girls) and 20 average-ability control participants (12 boys, 8 girls) were matched for age (11–14 years), socioeconomic status (upper-middle class), and degree of right-handedness (as measured by the Edinburgh Handedness Inventory; Oldfield, 1973). Hand preference was monitored in light of a potential difference in the degree and direction of hemispheric organization between right-handed and left-handed individuals (see O'Boyle & Hellige, 1989), with the former being highly lateralized and the latter being predisposed toward more bilateral representation of functions (cf. O'Boyle & Hoff, 1987). By controlling for hand preference (and thus presumably equating underlying patterns of lateralization), it was possible to attribute any lateral difference between the groups in dichotic listening performance to their intellectual ability level rather than their hand preference per se.

By way of experimental details, the six stop consonants—*pa, ta, ka, ba, da,* and *ga*—served as stimuli, producing 30 dichotic pairs that were presented in two sets, for a total of 60 trials. A trial consisted of two syllables presented simultaneously, one to each ear with equal loudness and time duration, and the participant was required to circle from a set of six syllables, the two that were heard. Syllable pairs were simultaneous within +/– 2.5 msec with a 6 sec interval between pairs, and they had an average auditory intensity level of 70 dB, +/– 2.5 dB. Headphones were reversed after the first set of trials to control for any potential confounds in presentation (e.g., one headphone being louder or clearer than the other, resulting in some artifactual asymmetry).

The dependent variable of interest was the mean number of correct syllable identifications for each ear/hemisphere. A 2 (group: gifted vs. control) × 2 (sex: male vs. female) × 2 (set: first vs. second) × 2 (hemisphere: LH vs. RH) mixed-design analysis of variance (ANOVA) revealed (a) that Set 2 performance was more accurate than Set 1 (i.e., a practice effect), (b) that the right ear–LH was superior to the left ear–RH, and (c) that gifted participants recognized significantly more syllables than did average-ability participants. Of particular importance was the presence of a significant three-way interaction among these factors. On Set 1 trials, there was no hemispheric recognition asymmetry between the two groups. However, on Set 2 trials, the average-ability participants showed the prototypical LH advantage, whereas gifted participants were equally able using either ear. This finding suggests that the functional organization of the gifted brain is somewhat different in that the gifted RH appears to be unusually involved, and uncharacteristically successful, in the performance of this language-oriented task. In fact, post hoc analyses revealed that, for gifted participants, the nonspecialized RH was equivalent in accuracy to the linguistically specialized LH (see Figure 1).

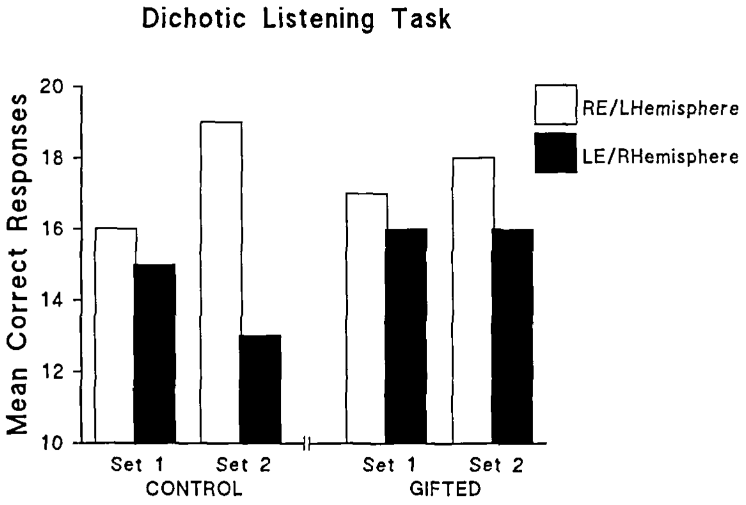

FIGURE 1 Mean number of syllable identifications for gifted and control participants as a function of ear/hemisphere and set (adapted from O'Boyle & Benbow, 1990a, Experiment 1).

CONCURRENT FINGER-TAPPING

The O'Boyle and Benbow (1990a, Experiment 1) finding was, to our knowledge, the first empirical support for the idea that the functional organization of the gifted brain may be different than that of average-ability individuals, specifically in regard to the apparent enhanced involvement of the RH during basic information processing. It was, however, only a single study, and further investigation was needed to confirm such theorizing. Thus, a different paradigm was employed in an attempt to provide converging evidence in support of our enhanced RH hypothesis. In this regard, O'Boyle, Gill, Benbow, and Alexander (1994) conducted a concurrent finger-tapping experiment in which 24 gifted and 24 average-ability male adolescents were asked to tap a keypad for 10 sec (first with one hand and then the other) while either remaining silent (i.e., the baseline condition) or reading a paragraph aloud (i.e., concurrent verbal load).

In light of the Functional Cerebral Distance Principle proposed by Kinsbourne (1975), a significant reduction in right-hand tapping rate was expected in the concurrent verbal task condition relative to baseline. The logic here is that the LH would be forced to split its cortical resources between the linguistic processing of the paragraph and motor control of the right hand. Left-hand tapping, however, would be virtually unaffected by the concurrent verbal load as the RH, though in control of left-hand tapping, bears little or no responsibility for verbal processing of the paragraph. This differential interference pattern has in fact been reported by other experimenters employing a variety of concurrent linguistic tasks (e.g., Hellige & Kee, 1990; Hellige & Longstreth, 1981; Kinsbourne & Hiscock, 1983; van Strien & Bouma, 1988). In our study, the prediction was that average-ability participants would show the prototypical right-hand–LH tapping reduction during concurrent verbal processing, but that gifted individuals would exhibit a reduction in tapping rate for both hands, reflecting a bilateral pattern of hemispheric involvement—a pattern similar to that observed in their dichotic listening for syllables performance. Such a finding would again suggest that enhanced RH involvement during information processing is particularly related to intellectual giftedness.

In the O'Boyle et al. (1994) study, the dependent variable of interest was the reduction in tapping rate for the left and right hands during the concurrent verbal load as compared to baseline. A 2 (group: gifted vs. average) × 2 (hand: left vs. right) × 2 (load: baseline vs. verbal load) mixed-design ANOVA on the mean number of taps per unit time revealed (a) that the gifted group tapped significantly faster than the average-ability group, (b) that the right hand tapped faster than the left hand (all participants were right-handed), and (c) that tapping was faster at baseline than during the concurrent verbal load condition. A significant Hand × Load interaction was also obtained, indicating that the performance of the concurrent verbal task reduced tapping more for the right hand than the left hand, irrespective of group membership. But, of particular importance, was the finding of a significant Group × Hand × Load interaction. Post hoc evaluation of this effect revealed that the average-ability group showed the anticipated right-hand–LH tapping reduction, with the left-hand–RH being virtually unaffected. However, the gifted group showed a significant reduction in tapping rate for both hands—one that was essentially equivalent in magnitude, suggesting bilateral involvement in the performance of this language-related task. In contrast to the unimanual right hand–LH interference observed in the average-ability participants, this bilateral pattern suggests enhanced RH processing involvement in the gifted group (see Figure 2).

These findings dovetail nicely with the previously obtained bilateral involvement of the hemispheres in gifted participants during dichotic listening for syllables, and the results from both studies are congruent with our enhanced RH hypothesis. Interestingly, Obrzut, Hynd, Obrzut, and Leitgeb (1980) used a similar concurrent verbal finger-tapping task to demonstrate an excessive decrement in right hand–LH tapping in individuals with learning disabilities. This later finding, when juxtaposed with our own results, suggests a continuum of hemispheric asymmetry in special populations, with the individuals with learning disabilities characterized as having excessive reliance on LH processing, and the gifted by enhanced RH involvement, resulting in a more bilateral pattern of hemispheric engagement.

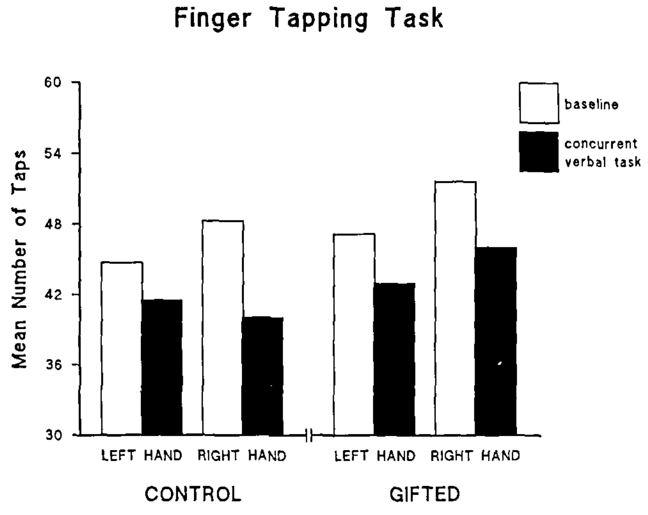

FIGURE 2 Mean number of taps per unit time for gifted and average-ability participants using their left and right hands at baseline and in the verbal load condition (adapted from O'Boyle et al., 1994).

CHIMERIC FACE PROCESSING

The data from our dichotic listening and concurrent finger-tapping studies provide converging evidence for the notion of enhanced RH involvement in basic information processing as a characteristic of the gifted brain. However, these tasks represented just two of many that might be used to index patterns of lateralization, and further studies were required to reach any strong conclusions. In light of this fact, an experiment (O'Boyle & Benbow, 1990a, Experiment 2) was conducted that more directly tested the involvement of the gifted RH using a different experimental technique—namely the Free-Vision Chimeric Face Task (CFT) as developed by Jerre Levy and her colleagues (Levy, Heller, Banich, & Burton, 1983). In the CFT, an individual's face is photographed in both a neutral expression and while smiling. Subsequently, the photo is cut midsagittally, and a chimeric stimulus is created by connecting the leftside smile to the rightside neutral half-face, and vice versa. In the CFT, the participant is asked to compare each chimeric face with its mirror image and to judge which of the two is the "happier" (see Figure 3).

As previously noted, the RH is thought to bear primary responsibility for the processing of human faces and is known to play the predominant role in the determination of the emotional affect the faces may convey (Sackheim & Gur, 1978). Thus, when the side of the chimera expressing the emotion is contralateral to the RH (i.e., the leftside smile–rightside neutral composite), the subjective impression is that it is indeed happier than its mirror-reversed counterpart. According to Levy et al. (1983), the extent of RH engagement during performance of this task is indexed by the number of times that the leftside smile–rightside neutral chimera is selected as compared to its mirror-reversed counterpart. In our study—given the specialized connection among face processing, the extraction of facial affect, and the RH—we anticipated that both gifted and average-ability participants would be RH biased in their choices (i.e., selecting the leftside smile–rightside neutral composites more often) but that the gifted, having already shown an unusual reliance on their RH during dichotic listening and concurrent verbal finger-tapping, would be significantly more RH engaged and thus more biased in their selections.

Concerning details of procedure and method, 60 gifted (42 boys and 18 girls) and 20 average-ability (12 boys and 8 girls) participants were run as a group, using overhead projections of the chimeric stimuli. Eighteen chimeric faces were created, and each was paired with its mirror image and rated twice for a total of 36 trials. Each face was 60 cm square and seen for 10 sec at a viewing distance of 3 m. The dependent variable of interest was the number of left-biased and right-biased choices, which was quantified as in Levy et al. (1983) by using the formula $(R - L)/36$, where R is the number of times the leftside smile–rightside neutral composite was chosen and L is the number of times the rightside smile–leftside neutral composite was selected. The value 36 corresponds to the total number of chimeric

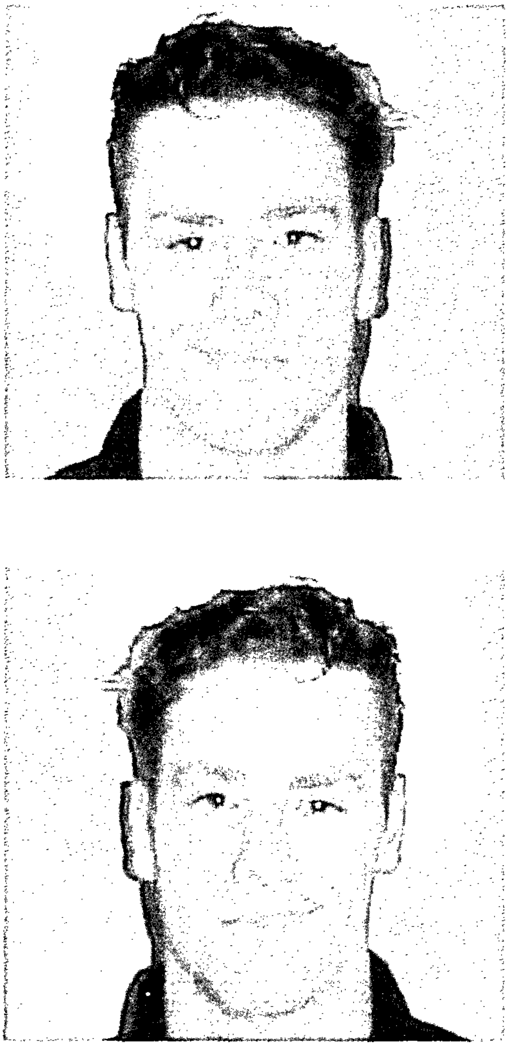

FIGURE 3 An example of a chimeric face trial.

pairs presented. When using this formula, a negative quotient is indicative of RH involvement in the task, and a positive quotient suggests LH involvement.

Median laterality quotients were computed for both groups (gifted = –.37; average ability = –.12) and subsequent one-tailed *t* tests revealed that both groups were significantly RH biased in their choices. Moreover, a 2 (group: gifted vs. average) × 2 (sex: male vs. female) between-participants ANOVA performed on the laterality scores confirmed that the gifted had a significantly stronger degree of RH involvement relative to average-ability participants. Notably, sex was not significant in the main, and it did not reliably interact with group membership (see Figure 4).

These findings support the notion that the RH of the gifted is more actively involved than in average-ability participants during chimeric face processing. And, interestingly, the sex of the participant was not a distinguishing factor, as both gifted boys and girls exhibit this enhanced engagement of RH resources. Notably, the group differences obtained in this study, as well as those from the dichotic listening and finger-tapping experiments, are based on performance in tasks that do not necessarily engage higher order thinking or reasoning per se, the types of processes that are typically associated with intellectual giftedness. Thus, the question remained how (and if) this enhanced RH involvement was actually related to precocity.

To address this issue, we correlated the laterality quotient obtained for each gifted individual with their combined SAT–M and SAT–V score. The rationale here is that if enhanced RH engagement contributes to giftedness, the degree of involvement of the RH in the chimeric face task should be predictive of their SAT performance. A Pearson product-moment correlation between these two variables was found to be significant ($r = -.29, p < .02$), indicating that the more negative the laterality quotient (and thus the greater the involvement of the RH), the higher the combined SAT score. This finding lent further support to our notion that enhanced engagement of RH resources contributes to an extreme level of intellectual ability.[1]

EEG INDICATORS OF GIFTEDNESS

An additional piece of the giftedness puzzle has been investigated recently. Given the behavioral evidence that RH resources are more readily engaged in the gifted, was it possible to obtain more direct physiological evidence to corroborate this notion? For example, could it be shown that at the neural level, brain activation is also enhanced in the RH of precocious individuals?

With this in mind, we (O'Boyle, Alexander, & Benbow, 1991) conducted an investigation in which gifted and average-ability participants performed the previously described CFT while brain wave activity (EEG) was monitored over eight cortical locations—the frontal, occipital, parietal, and temporal lobes of the LH and

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[1] Somewhat surprisingly, when the laterality quotients were correlated with each of the SAT subscales (i.e., Math and Verbal), the relation was significant only for the SAT–V; the correlation with SAT–M scores was nonsignificant. This probably relates to the fact that in the latter case, there is a severe range restriction associated with SAT–M performance, with virtually all of the gifted participants having extremely high SAT–M scores. Performance on the SAT–V, though also quite high, was more normally distributed, thus allowing a significant correlation to manifest itself.

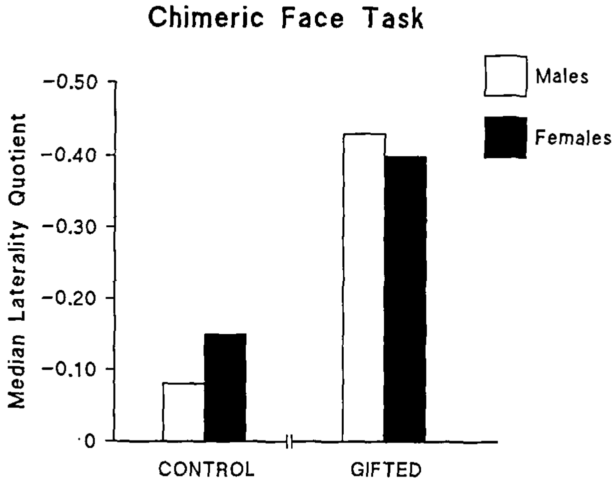

FIGURE 4 Median laterality quotients for gifted and average-ability male and female participants during chimeric face processing (adapted from O'Boyle & Benbow, 1990a, Experiment 2).

RH. Alpha activity was the waveform of interest, one that is typically characterized as 8–12 Hz resting potential and reflecting a neutral cognitive state. In contrast, a reduction in Alpha power is thought to be indicative of enhanced cortical activation in the brain region located beneath the electrode positioned on the scalp (Gevins, 1983; Giannitrapani & Murri, 1988).

In this study, two types of predictions were made:

1. At the behavioral level, we expected to replicate our earlier result, with the gifted (as compared to average-ability participants) more often choosing the leftside smile–rightside neutral composite as being the happier face.

2. At the physiological level, we anticipated that both groups would show more RH than LH brain activation; however, the gifted would exhibit significantly greater RH activation than the average-ability group in keeping with their enhanced utilization of RH resources.

By way of methodology, six gifted and eight average-ability, right-handed adolescents performed the CFT as previously described, while ongoing EEG activity was recorded over the four lobes of each hemisphere. Participants were seated in a sound-attenuated and electrically shielded chamber and instructed to close their eyes. Upon request of the experimenter, participants opened their eyes and viewed a pair of chimeric faces; they subsequently were required to judge which of the two was the "happier." The eight surface electrodes were positioned at scalp locations, Fp1, Fp2, T3, T4, P3, P4, 01, and 02 (Jasper, 1958) and linked earlobes

(A1 + A2) served as reference leads. Electrode impedance was maintained below 10 kΩ and the eight channels of the EEG were calibrated to a standard of 50μV. The recording epoch was 2 sec per trial, and EEG was digitized on-line at 100 samples per sec. Eye-blinks were edited from the recording, and Alpha activity was isolated using an 8–12 Hz bandpass filter. All power spectral analyses were performed on these filtered recordings (for further details, see O'Boyle et al., 1991).

Behavioral Data

Using the previously described formula (Levy et al., 1983), laterality quotients were computed to ascertain relative LH and RH involvement in this replication of the CFT. As compared to our previous study, the gifted group showed an even stronger tendency to select the leftside smile–rightside neutral chimera as the happier face (–.52), indicating an even greater reliance on RH resources in the performance of this task. Interestingly, the degree of this bias exceeds that reported by Levine and Levy (1986) for college-age individuals, suggesting that the gifted, relative to others their age, may be at a more advanced state of brain activation and functional organization. Somewhat surprisingly, the average-ability participants showed a nonsignificant bias toward LH involvement in this task (+.09).[2]

EEG Data

For baseline EEG data, using the formula $[(R-L)/(R+L)]$ allows for Alpha power at homologous locations over the RH and the LH to be directly compared. Mean Alpha power at each of the eight brain sites was evaluated using a 2 (group: gifted vs. average) × 4 (location: frontal, temporal, parietal, occipital) mixed-design ANOVA. The results of this analysis revealed a significant main effect for group, showing that, at rest, the gifted were significantly more active than the average-ability group, particularly at the left temporal lobe. By way of speculation, this enhanced LH activation may be related to the hypothesized executive function (or *metacontrol*) sometimes ascribed to the LH in the coordination and allocation of cortical resources (see Gazzaniga, 1985; Hellige & Mitchimata, 1989; Luria, 1973; O'Boyle et al., 1991). To assess brain activity during performance of the CFT, the formula $[(R-L)/(R+L)$ Baseline$] - [(R-L)/(R+L)$ Task$]$ was employed. This

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[2] It should be noted that there were only eight individuals composing the control group, and one of them selected the rightside smile–leftside neutral composite (the opposite pattern) nearly 100% of the time. If this participant is excluded from the calculations, the average-ability group then shows the expected negative mean laterality quotient, indicative of enhanced RH involvement.

ratio indicates the extent to which Alpha power is reduced during task involvement, with significant reductions at a given brain site suggesting that this region is actively involved in chimeric face processing. As can be seen in Figure 5, the analysis performed on these mean Alpha power reductions indicate that when gifted participants are engaged in the CFT, the initial LH baseline activational state shifts dramatically toward RH activation—one that is localized to the right temporal lobe. Notably, this is the very region implicated by unilateral brain-damage studies as crucial to face processing (Kolb & Whishaw, 1990). This orchestrated shifting of activation to the region most likely to be involved in successful performance of a given task could be a physiological characteristic of the gifted brain. In fact, it may be that this coordinated activational shifting is a manifestation of what Sternberg (1986) identified as the superior metacognitive knowledge characterizing gifted thinking.

Somewhat curiously, the laterality quotient produced by the average-ability group was indicative of mixed hemispheric involvement in the task, and in keeping with this fact, the EEG data also suggested more bilateral activation of their brain during performance of the CFT. Although the behavioral and electrophysiological data are consistent, the finding remains anomalous in light of other research and requires further investigation (but see footnote 2).

In summary, the conclusion to be drawn from the O'Boyle et al. (1991) study is that the gifted brain appears to be characterized by enhanced RH activation during information processing and has the unique capacity to switch such activation from one brain locale to the next in a coordinated and orchestrated manner, as evidenced

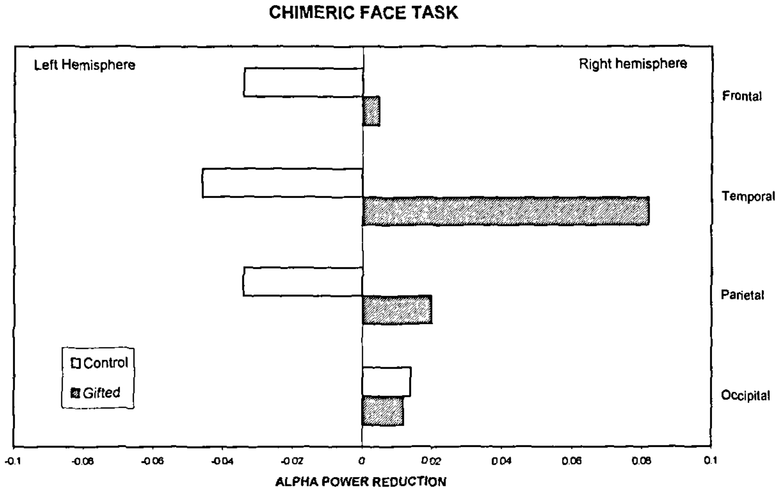

FIGURE 5 Alpha power reductions (μV^2/Hz) for gifted and average-ability participants during chimeric face processing (adapted from O'Boyle et al., 1991).

by the impressive shift from a generalized LH activation at rest, to focalized right temporal lobe activation during chimeric face processing. To the extent that the average-ability data can be accurately interpreted, they are seemingly as likely to shift left as right, perhaps reflecting a more underdeveloped physiological or functional brain state.

SEX AND LATERALITY DIFFERENCES IN BRAIN ACTIVATION/INHIBITION

By way of new and previously unpublished data, we now report on a study designed to directly investigate the possibility of differential brain activation and inhibition patterns in gifted male and female adolescents. As previously discussed, both physiological and psychological studies indicate that specialized cognitive processes may be lateralized to one or the other hemisphere of the human brain, with most language functions localized to the LH and the visuospatial capacities localized to the RH (see the reviews cited earlier). Moreover, biological sex has been suggested to influence brain lateralization with this prototypical left/right specialization being more pronounced in men than in women (Hellige, 1990, 1993; McGlone, 1980, O'Boyle & Hellige, 1989). As previously indicated by our own work, patterns of laterality seem to vary as a function of intellectual level and thus may be related to the sex differences in cognitive abilities found among the gifted (O'Boyle et al., 1991; O'Boyle & Benbow, 1990a, 1990b; O'Boyle et al., 1994). For example, not only are there more male than female adolescents at the extreme end of the gifted distribution in mathematics (Benbow, 1988), but precocious girls also tend to exhibit lower spatial and mechanical reasoning abilities than gifted boys (Benbow, 1988; Lubinski & Benbow, 1992; O'Boyle & Benbow, 1990a, 1990b). In this context, it is conceivable that patterns of hemispheric lateralization are affecting levels of intellectual functioning and thus may underlie some of the sex-related ability differences found therein.

Recall that in the O'Boyle et al. (1991) study, we used both behavioral measures and EEG recordings during chimeric face processing to investigate patterns of brain activity in gifted and average-ability male adolescents. We found that during CFT performance, right temporal lobe activation was obtained in gifted participants, whereas those of average ability exhibited a mixed pattern of engagement. Although these results suggested that enhanced RH activation is uniquely related to intellectual precocity, this conclusion must be tempered somewhat by the fact that a comparable female group was not studied, and these findings had not been replicated using a larger sample (i.e., the O'Boyle et al. study used only 14 participants in total, with 6 of them being gifted). Because previous research has reported several differences between men and women on a variety of cognitive measures (Halpern, 1992; Maccoby & Jacklin, 1974) and lateralization tasks (Harshman & Hampson, 1987; Kimura, 1992; Levy & Reid, 1976; O'Boyle & Hoff, 1987), we felt it was important to assess patterns of brain activity in both sexes during verbal and visuospatial processing, thus broadening our knowledge base concerning the physiological substrate of precocity. In the following study, gifted male and female adolescents performed the CFT and a comparable verbal task. In the latter, participants viewed word pairs and were asked to determine which of the two conveyed the happier sentiment. Along with behavioral measures, ongoing EEG recordings were also taken.

METHOD

Participants

A total of 35 participants took part in the word-processing task. In this condition, the gifted group consisted of 9 male and 10 female adolescents; the average-ability group (i.e., students from a local junior high school not qualifying for the gifted program) consisted of 10 male and 6 female adolescents. A total of 43 participated in the CFT. In this condition, the gifted group comprised 9 male and 13 female adolescents; the average-ability group consisted of 11 male and 10 female adolescents. All participants were 12 to 14 years old and right-handed, with no left-handed relatives. Hand preference was assessed by a 10-item questionnaire designed to determine the hand used when performing various motor tasks like writing, drawing, and throwing. All participants were screened for neurological damage, neuropsychological disorder, and current medication use. An intellectual profile of this gifted group appears in Table 1. These measures verify that our precocious participants represent the top ½% in overall intellectual ability when adjusted for age, and they reflect the sex differences typically found. Informed consent was

TABLE 1
Means and Standard Deviations for the Cognitive Abilities Tests

		SAT–Verbal (Max = 800)		*SAT-Math (Max = 800)*		*Mental Rotation*[a] *(Max = 40)*		*Advanced Raven's*[b] *(Max = 36)*	
Sex	*Age (Years)*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Male	13.09	426	84	598	103	29.2	11.0	25.2	4.3
Female	13.54	419	93	496	70	21.2	8.5	25.9	3.9

Note. Scores of gifted participants when taking tests designed for adults or late adolescents (e.g., mean test scores for British University students on the Advanced Raven's is 21).

[a] Vandenberg and Kuse (1978) Mental Rotation Test.

[b] Advanced Raven's Progressive Matrices (Raven, Court, & Raven, 1993).

obtained from the participants and from their parents prior to participation in the study.[3]

Materials and Procedure

Thirty-six word pairs and 36 chimeric face pairs served as stimuli. All pairs were presented using a slide projector and viewed at a distance of 1.25 m. Participants received a total of 52 stimulus presentations for each condition in which they participated. Each task was divided into four blocks of 13 trials each. A block consisted of four blank baseline slides, followed by either 9 word pairs or 9 chimeric face pairs. Participants were seated in a reclining chair located within an electrically shielded, sound-attenuated chamber and were told to close their eyes. A slide was presented on the viewing screen, and the experimenter cued participants with an "eyes open" command, which initiated a 2 sec EEG recording epoch. During the baseline condition, participants were asked to look at the center of a blank slide. For word stimuli, they were instructed to choose which of the two words (e.g., *vomit* or *smile*) conveyed the more pleasant sentiment, whereas for the chimeric face stimuli, they were asked to judge which of two appeared to be the happier.

Word stimuli were selected on the basis of pleasantness ratings in which the two words in each pair differed by at least 2 points on a 7-point scale (Silverstein & Dienstbier, 1968). Also, each pair was constructed of words with the same number of letters and equivalent print frequency (Thorndike & Lorge, 1944). The linguistic processing of such verbal stimuli is thought to be mediated primarily by the LH. For the chimeric face stimuli, as described earlier, each chimera consisted of two joined half-faces, either a leftside smile–rightside neutral composite, or a rightside smile–leftside neutral composite of the same individual. In this version of the CFT, each chimera was paired with its mirror image—once with a given face at the top of the display and its mirror image below and once with the positions reversed. As previously noted, when the side of the face expressing the smile is contralateral to the RH, that composite is reliably judged to be the happier of the two (Levy et al., 1983, O'Boyle & Benbow, 1990a, Experiment 2). This bias is thought to reflect the specialized capacity of the RH for complex visuospatial processing and the determination of facial affect (Sackheim, Gur, & Saucy, 1978).

As in O'Boyle et al. (1991), during cognitive engagement, EEG activity was monitored from the left and right frontal (Fp1, Fp2), temporal (T3, T4), parietal (P3, P4), and occipital (O1, O2) sites (Jasper, 1958), using Grass amplifiers and an

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[3] A total of 14 participants were excluded from participation. Evidence of left-handedness resulted in 6 gifted and 5 average-ability participants being excluded from the study, 2 average-ability participants were disqualified because of current medication use, and 1 gifted individual refused to perform the required task. At completion of the study, participants were debriefed and offered paper records of their EEG.

ECI Electro-Cap (Blom & Anneveldt, 1982).[4] Participants' behavioral responses were hand-recorded on an answer sheet.

RESULTS

Statistical analysis of the behavioral data revealed no significant differences between the groups or sexes for correctly determining which word conveyed the more pleasant sentiment (gifted = 95%; controls = 92%). Performance in the CFT was evaluated as in Levy et al. (1983) by tabulating the number of right-biased and left-biased choices. A laterality quotient was computed for each participant using the same formula $(R - L)/36$ as previously described, where R is the number of times the rightside smile–leftside neutral face composite was chosen and L is the number of times the leftside smile–rightside neutral chimera was selected. The denominator is the total number of trials. Recall that a positive value reflects LH involvement in the task, and a negative value is indicative of RH involvement.

Planned comparisons were performed on the obtained mean laterality quotients. The results of these analyses revealed that the gifted group showed significantly greater RH involvement in the task than did average-ability participants (gifted = –.48; average = –.16; $p < .02$). Gifted boys (–.56) were significantly more RH biased ($p < .05$) than average-ability boys (–.17), whereas gifted girls (–.43) did not differ from average-ability girls (–.16). Notably, for those gifted participants who performed the CFT and had test scores ($n = 20$), their laterality quotient correlated significantly with their Advanced Raven's Progressive Matrices performance ($r = -.46$, $p < .05$). Essentially, the more negative the laterality quotient (and thus the greater the RH involvement in the CFT), the higher their score on this nonverbal measure of general intelligence. The correlations of laterality quotient with SAT–V (–.10), SAT–M (–.33), and Mental Rotation (–.23) scores, although in the same direction, were not significant.

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[4] All leads were referenced to linked ear lobes (A1 + A2), and electrode impedance was below 10 kΩ. Each of the eight channels of the polygraph was calibrated to a standard of 50 μV. The EEG was digitized on-line at 100 sweeps per sec and stored on computer disc. During data collection, the EEG was displayed on a computer screen and edited for eye blink and other muscle movement. Trials contaminated with either artifact were excluded from all analyses. Such trials never exceeded 23% of the total presentations, yielding a minimum of 28 artifact-free EEG epochs for each type of task. EEG data were filtered to 8–12 Hz, and all analyses were performed on this Alpha bandwidth. Within each condition, spectral power was calculated for each trial, and the average of the spectra was computed, producing 16 mean power values for each participant. These means were defined by the orthogonal combination of 2 Stimulus Types (blank vs. task), 4 Locations (frontal, temporal, parietal, occipital), and 2 Hemispheres (left vs. right).

To assess shifts in EEG activity between baseline and task conditions, percentage change values were calculated for each electrode location over the RH and LH. This was accomplished by using the formula PC = [(Base – Task) / Base] × 100, where Base is the Alpha power value at a given location in the baseline condition and Task is the Alpha power value at the same location during word or face processing. A positive PC represents percentage activation (reduced Alpha power) and a negative PC represents percentage inhibition (increased Alpha power). It should be noted that Mean Log_{10} transformations of these data were used when calculating PC values to ensure homogeneity of variance. Subsequently, a 2 (ability) × 2 (sex) × 2 (hemisphere) × 4 (location) mixed-design ANOVA was performed, and a Newman–Keuls post hoc testing procedure ($p < .05$) was used to evaluate all significant effects.

Changes in hemispheric activation and inhibition for each task relative to baseline are displayed in Figures 6 and 7. During word processing (Figure 6), gifted participants exhibited greater brain activity than did average-ability participants (Ability), $F(1, 31) = 4.35$, $p < .05$. Also, precocious individuals were more active at the frontal lobes, whereas average-ability participants were more active at the temporal lobes (Ability × Location), $F(3, 39) = 3.29$, $p < .02$. No other effects were found to be statistically reliable. During chimeric face processing (Figure 7), the frontal lobes were more active than the other three cortical regions for all groups (Location), $F(3, 117) = 5.96$, $p < .001$. Collapsed across location and sex, the gifted generally produce LH inhibition during face processing, whereas those of average ability show RH inhibition (Ability × Hemisphere), $F(1 ,39) = 11.90$, $p < .0015$. Adding sex as a factor, and collapsing across ability level, male individuals show lateralized activity that is most prominent at the temporal lobes (though on opposite sides of the brain for gifted as compared to controls), whereas female individuals are primarily active at the frontal lobes (Sex × Location × Hemisphere), $F(3, 117) = 2.71$, $p < .05$. Of particular interest is the unique pattern of hemispheric engagement exhibited by gifted male participants who, during chimeric face processing, demonstrate significant left temporal lobe inhibition (Ability × Sex × Location × Hemisphere), $F(3, 117) = 2.70$, $p < .05$.

DISCUSSION

The results of the present study indicate that different patterns of brain activation and inhibition characterize gifted and average-ability adolescents, with several differences being hemisphere and sex specific. During word processing, gifted participants were more active than controls and appeared to rely on different cortical areas when determining which of two words conveys the more pleasant sentiment: The gifted activate frontal regions, whereas those of average ability activate

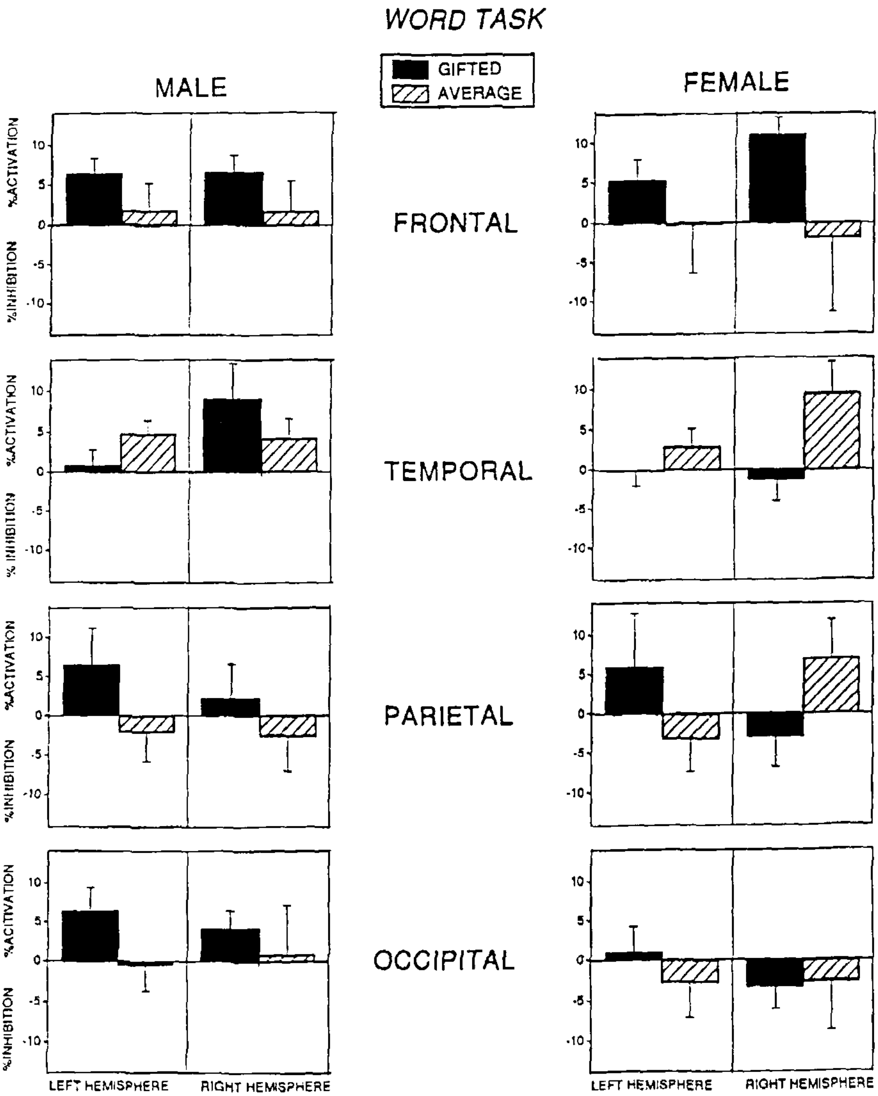

FIGURE 6 Percentage change of brain activation and inhibition for word processing.

temporal regions. The importance of this enhanced frontal lobe functioning in the gifted is not yet clear, though it is in keeping with other neuropsychological findings suggesting that the frontal lobes mediate high-level intelligence (Chen & Buckley, 1988; Dempster, 1991; Pribram & Luria, 1973, Stuss, 1992).

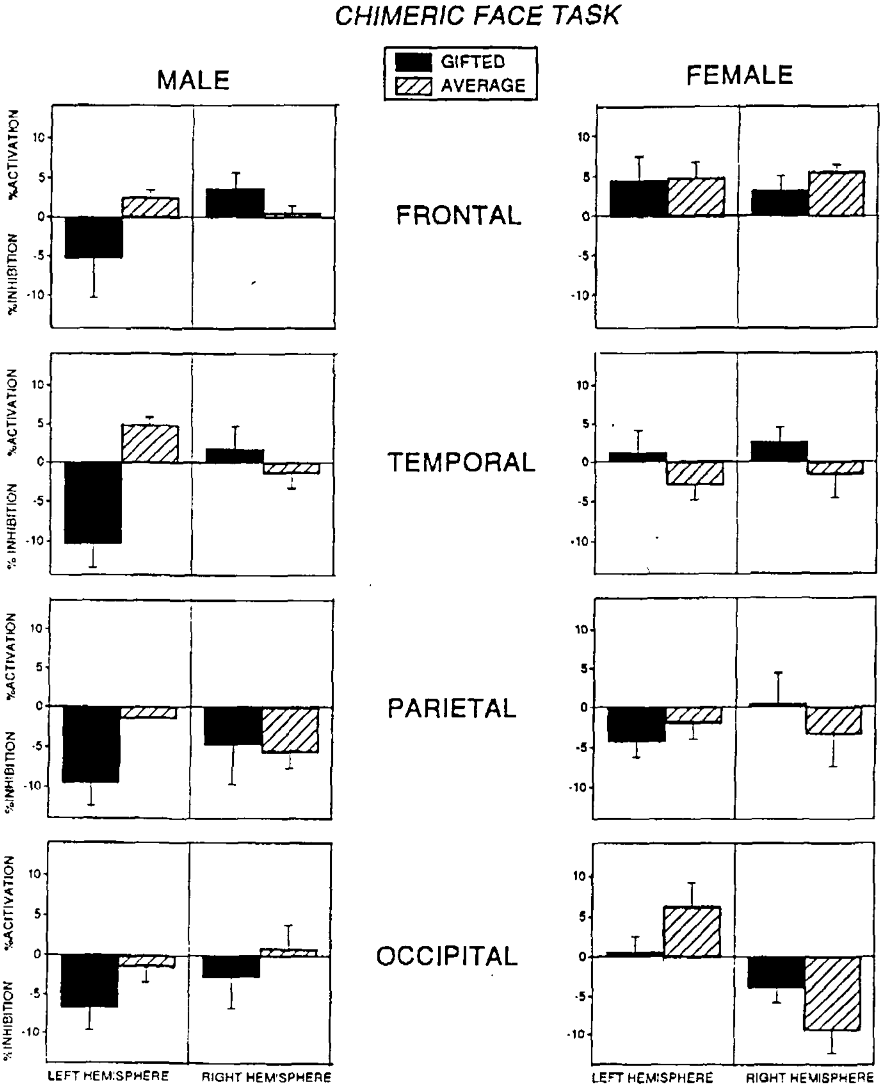

FIGURE 7 Percentage change of brain activation and inhibition for chimeric face processing.

During the CFT, a unique pattern of brain activity was found in gifted male adolescents. When judging which of two chimeras is the happier, the latter exhibit significant LH inhibition, a pattern of disengagement allowing the RH to play the predominant role in processing the face composites and analyzing them for their affective content (cf. Sackheim et al., 1978). Thus, it appears that an additional electrophysiological characteristic of the gifted brain (at least in boys) is the ability to selectively inhibit cortical regions that are unlikely to be involved in the specialized processing requirements of the task at hand.[5] The net effect of such inhibition may be to minimize undesirable cross-talk between critical (e.g., the right temporal lobe) and other less critical (or unnecessary) cortical locations that might interfere with subsequent processing and performance. The fact that female participants of both groups were somewhat more bilaterally engaged during face processing may reflect a more diffuse state of hemispheric specialization and functional brain organization.

At the behavioral level, gifted individuals (particularly boys) were more likely than average-ability participants to choose the leftside smile–rightside neutral composites as the happier face—a converging indicator of enhanced RH activation. Notably, the degree of RH involvement exhibited by gifted participants of either sex was predictive of their general intelligence—the greater the RH engagement, the higher their manifest intellectual ability as measured by the Advanced Raven's Progressive Matrices performance (and to a lesser extent, by their SAT and Mental Rotation performance). These findings are in keeping with our earlier research and reinforce the notion that enhanced RH involvement during information processing is a physiological correlate of gifted brain functioning.

Although it appears that differences in brain activation and inhibition are related to intellectual precocity (at least in boys), the origins of this association are not yet known. It should be noted that EEG activity patterns are subject to change during childhood development (Thatcher, Walker, & Giudice, 1987) and may be biologically mediated such that gifted boys (as compared to girls) are more readily able to access, implement, and coordinate cortical resources. As speculated elsewhere in this article, these sex-related patterns of activity may emerge as a result of the developmental influence of prenatal exposure to high levels of androgens (Geschwind & Behan, 1982). Specifically, the application of testosterone during critical stages of early maturation is known to have a masculinizing effect on the mammalian brain such that if a female fetus is exposed to testosterone, both brain and genitalia become masculinized (Kelly, 1991). Given that testosterone can modify the relative development of the two cerebral hemispheres (Galaburda, Corsiglia, Rosen, & Sherman, 1987), sex differences in brain activity among the gifted may be a by-product of this prenatal testosterone exposure. Such speculation does not minimize environmental factors, however, as they are necessary for optimal development of any biologically based predisposition. Regardless of origins, however,

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[5] In light of such theorizing, one might have expected that gifted male participants would also inhibit RH functioning during word processing. However, this task not only involves linguistic processing (predominantly a LH function), but also requires determination of emotional affect (predominantly a RH function) which may account for the absence of any significant RH inhibition.

the data from this study indicate that intellectual precocity is mediated by activation and inhibition patterns that generally differ in male and female adolescents.

CONCLUSIONS

In this article, we have attempted to integrate a series of studies, conducted over the last several years, designed to evaluate the hypothesis that extreme intellectual precocity is related to enhanced involvement of the RH during basic information processing (Benbow, 1986) as well as to superior coordination of cortical resources between the hemispheres when engaged in intellectual tasks (O'Boyle et al., 1991). The data presented here were obtained using a variety of neuropsychological methods, including dichotic listening, concurrent finger-tapping, and word and chimeric face processing, and they are supplemented by an electrophysiological measure—namely EEG recordings. In gifted participants, the more involved the RH during information processing, the greater their manifest intellectual ability as evidenced by their SAT and Raven's Progressive Matrices scores. Each of these findings provide converging support for our hypotheses, particularly in precocious male adolescents. Specifically, in gifted boys, there is strong evidence of high-level RH engagement during information processing, and their EEG data also reveal a finely tuned capacity for activating (or inhibiting) the very brain regions known to play (not play) specialized roles in the performance of a given task. As previously suggested, the orchestrated activational and inhibitory shifting by precocious boys may be a physiological manifestation of what Sternberg (1986) previously described as the superior metacognitive knowledge associated with gifted thinking processes. That is, precocious individuals are especially facile at knowing what steps to take in solving a given intellectual problem.

It is noteworthy that the EEG recordings for the gifted group indicate especially active frontal lobes. Recently, Alexander, Benbow, and O'Boyle (1995) found that overall frontal activity for gifted adolescents is comparable in spectral power to that of college students several years older, with whom they share equivalent levels of intellectual ability. No such pattern was found between college students and average-ability participants. Although the interpretation of this result is still tenuous, it is clearly in keeping with other neuropsychological findings suggesting that the frontal lobes mediate exceptional intelligence (Chen & Buckley, 1988; Dempster, 1991; Pribram & Luria, 1973, Stuss, 1992). By way of contrast, Morris, Obrzut, and Coulthard-Morris (1989) found increased temporal (rather than frontal) lobe activation in learning disabled participants, again suggesting that on a brain activation continuum, enhanced frontal activity is a uniquely important characteristic of intelligent (perhaps gifted) brain functioning.

Notably, Benbow's (1986) hypothesis of enhanced RH functioning as a characteristic of the gifted brain was put forward in the context of attempting to explain persistent sex differences in extreme mathematical reasoning ability (Benbow, 1988; Benbow & Stanley, 1980, 1983), which are typically accompanied by sex differences in spatial and mechanical reasoning ability as well (Lubinski & Benbow, 1992). We speculate that these sex-related patterns of cortical activity (and subsequent manifestations of ability) have emerged as a by-product of the developmental influence of prenatal exposure to high levels of androgens (Benbow, 1986; Geschwind & Behan, 1982). One must concede, however, that even though gifted individuals exhibit some physiological signs of such exposure (Benbow, 1986, 1988; O'Boyle et al., 1991; O'Boyle & Benbow, 1990a, 1990b), there is as of yet no detailed theory describing the influence exerted by this hormone on human brain development.

On a precautionary note, it is important to emphasize that none of our data speak directly to the nature vs. nurture issue or their interactive contributions to the development of intellectual precocity in either sex. Although our findings suggest that there is a biological basis for intellectual giftedness, the importance of environmental factors for optimal development of such a biologically based predisposition needs to be acknowledged. One should bear in mind, however, that responsiveness to environmental interventions need not be related to whether an attribute like precocity has biological or environmental origins (Meehl, 1992).

Finally, we believe that our data provide an integrative look at hemispheric functioning and brain activity in the intellectually gifted. There is strong evidence for an uncharacteristically high level of involvement of the RH in all types of cognitive task performance (including linguistic ones), as well as indications of enhanced coordination and allocation of cortical resources between the hemispheres during intellectual engagement. Each of these aspects of brain functioning seem particularly prominent in precocious boys, though somewhat less so in girls. Recently, using functional magnetic resonance imaging, Shaywitz et al. (1995) also identified sex differences in brain organization, particularly for language processing. Undoubtedly, through future use of sophisticated brain imaging techniques in conjunction with other behavioral tasks that encompass a wider and more complex range of intellectual functions, we should attain greater understanding of the nature of the sex differences, patterns of hemispheric laterality, and the associated brain processes that characterize the intellectually gifted.

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