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# Cerebellum in attention-deficit hyperactivity disorder

## A morphometric MRI study

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**Article abstract**—Clinical, neuroanatomic, neurobehavioral, and functional brain-imaging studies suggest a role for the cerebellum in cognitive functions, including attention. However, the cerebellum has not been systematically studied in attention-deficit hyperactivity disorder (ADHD). We quantified the cerebellar and vermal volumes, and the midsagittal areas of three vermal regions, from MRIs of 46 right-handed boys with ADHD and 47 matched healthy controls. Vermal volume was significantly less in the boys with ADHD. This reduction involved mainly the posterior inferior lobe (lobules VIII to X) but not the posterior superior lobe (lobules VI to VII). These results remained significant even after adjustment for brain volume and IQ. A cerebello-thalamo-prefrontal circuit dysfunction may subserve the motor control, inhibition, and executive function deficits encountered in ADHD.

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Attention-deficit hyperactivity disorder (ADHD) is characterized by deficits in attention, impulsivity, and motoric hyperactivity and is diagnosable as three subtypes in which inattention or hyperactivity-impulsivity is predominant or the two are combined.<sup>1</sup>

Neuropsychological studies suggest that the core deficit in ADHD is a failure to inhibit or delay response,<sup>2</sup> which is considered a central executive function.<sup>3</sup> The brain circuits associated with executive functions include the prefrontal cortex and the basal ganglia, which have been extensively studied in ADHD,<sup>4,5</sup> and the cerebellum.<sup>6</sup> Neuroanatomic results obtained with preclinical studies and quantitative brain MRI in humans as well as neuropsychological studies support the hypothesis that dysfunction in the frontal-striatal circuitry underlies ADHD.<sup>7-9</sup> Reported abnormalities include a lack of normal left-right asymmetry in caudate nuclei and anterior brain<sup>7,10</sup> and smaller globus pallidus volume.<sup>7,11</sup> Decreases in metabolism and blood flow in caudate and frontal lobe have also been found using functional neuroimaging.<sup>12</sup>

Recent human and preclinical studies suggested a cognitive role for the cerebellum.<sup>13</sup> For example, clinical and neuropsychological studies of patients with cerebellar lesions found visuospatial deficits and visuoconstructive task deficits.<sup>14</sup> The occurrence of mutism after posterior fossa surgery has long been known,<sup>15</sup> and deficits in learning and errors in both word- or number-generation tasks have been reported after cerebellar injury,<sup>16</sup> as have deficits in shifting attention,<sup>17</sup> figural memory,<sup>18</sup> or planning of action (Tower of Hanoi).<sup>19</sup> Reaction and movement time increases in both auditory and visual tasks suggest that cerebellar lesions may impair perceptual timing.<sup>20</sup>

Functional-neuroimaging studies in healthy volunteers have also provided evidence of cerebellar metabolism or blood flow activation in performing cognitive tasks involving simple verbal response selection,<sup>21</sup> chess problems,<sup>22</sup> a pegboard puzzle,<sup>23</sup> or timing processes.<sup>24</sup> Finally, animal studies using either cerebellar-lesioned rodents<sup>25</sup> or mutant mice<sup>26</sup> have implicated the cerebellum in motor and nonmotor learning.

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The cerebellum has rarely been studied in ADHD. Nasrallah et al.<sup>27</sup> using CT reported a qualitative size difference that did not reach significance. We noted that cerebellar volume was significantly smaller in 57 boys with ADHD compared with 55 healthy controls even after covariance for total brain volume ( $p = 0.05$ ). We considered this unexpected finding to be exploratory.<sup>7</sup>

Here, cerebellar volume, regional vermal mid-sagittal-area measures, and volumetric measures of the vermis and the posterior inferior lobe (lobules VIII to X) are described for a large sample of right-handed boys with ADHD and matched healthy controls. Based on recent reports reviewed above and our pilot findings, our hypothesis was that cerebellum development might also be affected in ADHD.

**Methods. Patients.** The 46 right-handed boys with ADHD were recruited for a drug treatment study and were included in a prior report.<sup>7</sup> Mean age was 11.7 years (range, 5.8 to 18.2). Inclusion criteria were clinical history of hyperactivity, impulsivity, and inattentive behavior at home and school and a Conners Teachers Hyperactivity Rating  $\geq$  95th percentile.<sup>28</sup> The Clinical Diagnostic and Statistical Manual of Mental Disorders, revised third edition (DSM-III-R) diagnosis<sup>29</sup> was confirmed using the Diagnostic Interview for Children and Adolescents.<sup>30</sup> Exclusion criteria were a full-scale Wechsler Intelligence Scale for Children-Revised (WISC-R)<sup>31</sup> score less than 80, chronic medical or neurologic pathology, or other primary psychiatric disorder.

Written assent and consent from the child and parents, respectively, were obtained as approved by the National Institute of Mental Health Institutional Review Board.

**Control group.** Forty-seven right-handed healthy boys were recruited from the community. Screening began with a parent interview by telephone supplemented by the Child Behavior Checklist<sup>32</sup> and the Conners Parent and Teacher Rating Scales.<sup>28</sup> Appropriate subjects then received a physical and neurologic examination including the 12 handedness items from the Revised Physical and Neurological Examination for Subtle Signs.<sup>33</sup> A psychiatric interview included the Child and Parent Diagnostic Interview for Children and Adolescents,<sup>30</sup> the Wide Range Achievement Test-Revised,<sup>34</sup> and the Vocabulary and Block Design subtests of the WISC-R. Exclusion criteria were physical, neurologic, or psychiatric history of abnormalities, or psychiatric disorder in any first-degree relative or in more than 20% of second-degree relatives.

**Methods. Image acquisition and analysis.** All subjects underwent MRI scan with the same 1.5-T General Electric (Oxford, England) Signa scanner. T1-weighted images with contiguous 1.5-mm-thick sections in the axial plane and 2-mm-thick sections in the coronal plane were collected using a three-dimensional spoiled gradient echo in the steady state (echo time = 5 msec, repetition time = 24 msec, flip angle = 45 degrees, acquisition matrix =  $256 \times 192$ , number of excitations = 1, field of view = 24 cm). Head alignment was standardized with two vitamin E capsules placed in each auditory meatus and a third one on the left inferior orbital ridge. These capsules, easily identifiable on MRI scan, were used to define the axial reference plane.

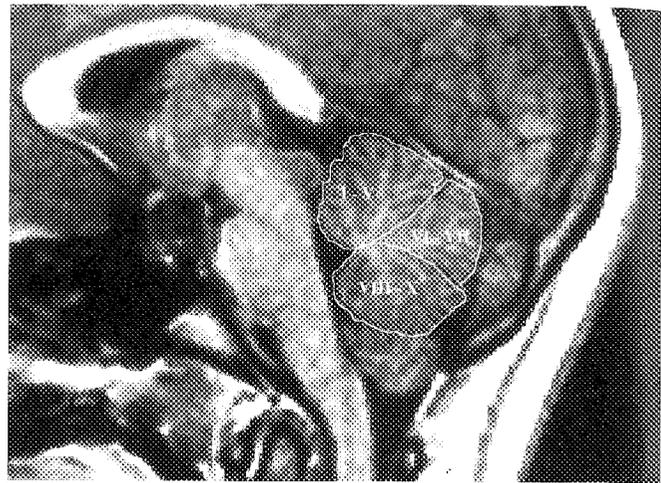


Figure 1. Vermis midsagittal area and subdivisions.

Sedation with either oral lorazepam (2 mg) or chloral hydrate (2 g) was used when needed for some ADHD subjects (approximately 20%). None of the control subjects was sedated. All scans were read as normal by a clinical neuro-radiologist.

Cerebrum and total cerebellar volumes were determined using an image analysis technique that models the surface as an elastically deformable structure and uses an energy minimization function to bring template surfaces into close correspondence with those of individual brains. The resulting image was then hand edited section by section to remove artifacts. Comparisons with postmortem brains and with volumes obtained from section-by-section hand-tracing measurements validated this method.<sup>35</sup> Intraclass correlations (ICC) for the volumes of edited cerebrum were 0.99 for interrater reliability and 0.92 for the automated-shelling procedure and volumes derived from slice-by-slice hand tracing.

The automated technique for quantifying cerebellar volume reported in our previous study at times omitted cerebellar tissue at the boundaries.<sup>7</sup> To address this source of error, all of the cerebellar volumes in this study were also hand edited, and only those subjects in whom the entire cerebellar volume was present were included for analysis ( $n = 57$ ). ICC were 0.98 for intrarater reliability, 0.84 for interrater reliability, and 0.89 for comparison between this automated-shelling procedure and the slice-by-slice hand-tracing method.

For area measures, the midsagittal plane was obtained from axial resliced sections using cerebellar structures as landmarks. This procedure has been found to be more accurate than using the cerebral midsagittal plane, which may not be aligned with the midline of the vermis.<sup>36</sup> Areas of the three vermal lobes were determined using the primary and the prepyramidal fissures and measured by hand tracing (figure 1). Interrater intraclass coefficient ICC were 0.83 for the anterior lobe (lobules I to V), 0.85 for the posterior superior lobe (lobules VI and VII), and 0.90 for the posterior inferior lobe (lobules VIII to X).

Vermis and posterior inferior lobe volumes were also determined by hand tracing using coronal slices. It was not possible to measure the volumes of anterior and posterior-superior lobes separately. The intrarater ICC was 0.94 for vermis volume and 0.91 for the posterior inferior lobe. The

**Table 1** Demographic characteristics of boys with ADHD and controls

Variable	ADHD (n = 46)*	Controls (n = 47)*	t-test	p Value†
Age (y)	11.7 ± 3.2	11.8 ± 3.0	0.04	0.96
Height (cm)	147.5 ± 18.3	151.5 ± 18.3	1.02	0.31
Weight (kg)	42.1 ± 17.6	44.3 ± 16.1	0.63	0.53
Tanner stage	2.2 ± 1.6	2.2 ± 1.5	0.14	0.89
WISC-R Vocabulary	11.8 ± 3.4	13.9 ± 2.8	3.32	<0.01
WISC-R Block Design	11.7 ± 3.7	13.4 ± 2.7	2.59	<0.01

\* Mean ± SD.

† All p values are two-tailed.

ADHD = attention-deficit hyperactivity disorder; WISC-R = Wechsler Intelligence Scale for Children-Revised.

interrater ICC were 0.94 and 0.95 for vermis and posterior inferior lobe, respectively.

All hand-tracing measurements were performed using NIH Image version 1.57; measurements were done masked to clinical characteristics.

**Statistical analysis.** Analyses by *t*-test were performed to compare groups by age, height, weight, Tanner stage, and IQ. Initial comparisons of brain measures between patients with ADHD and healthy controls were also done by *t*-test. All *p* values are two-tailed with a significance level of *p* = 0.05.

Because our groups differed in WISC-R subtest scores, the vermal area and volume measurements were further analyzed by ANCOVA using total brain volume and Vocabulary and Block Design WISC-R subtest scores as covariates.

Relations between anatomic data and behavioral variables were examined using linear regression analyses. Relations between cerebellar volumetric measures and previously reported morphometric measures were examined using Pearson product-moment correlations. Finally, stepwise regression with jackknife correction was performed to determine the usefulness of vermal measures in discriminating patients from healthy controls. The statistical software SAS, version 6.07, was used for all analyses.

**Results.** Demographic characteristics are summarized in table 1. Those with ADHD did not differ significantly from healthy controls in age, height, weight, or Tanner stage.

All subjects were right-handed. Although the mean WISC-R full scale score of the boys with ADHD was in the average range (108.5 ± 17.8, range, 83 to 148), their Vocabulary and Block Design subscales scores were significantly lower than those of the controls (*p* < 0.01).

Study results are summarized in table 2. Total cerebral volume was significantly smaller in the ADHD group compared with the control group by 6.1% (*p* < 0.01). Total cerebellar volume was 3.8% less in ADHD than in the control group (*p* = 0.06), but this trend was not significant after controlling for total brain volume. In contrast, the vermal volume was significantly smaller for the ADHD group than for the control group (8.5%, *p* < 0.0001). This difference remained significantly less after ANCOVA using total brain volume and Vocabulary WISC-R subtests scores as covariates (*p* = 0.01).

The posterior inferior lobe measures were also smaller in the boys with ADHD: 11.5% less in volume (*p* < 0.0001, ANCOVA *p* < 0.01) and 8.5% smaller in midsagittal area (*p* = 0.001, ANCOVA *p* < 0.05). It was not possible to measure the volumes of the anterior and posterior-superior lobes separately, but there were no statistically significant group differences in the midsagittal areas of these two regions. There was a nonsignificant trend for a smaller anterior lobe midsagittal area (*p* = 0.1). Results of ANCOVA analyses performed with Block Design WISC-R subtest scores or height as covariates did not differ.

Within the ADHD group, full-scale WISC-R IQ score

**Table 2** Total cerebral and cerebellar volumes and vermis midsagittal areas and volumes of 46 boys with ADHD and 47 matched controls

Variable	ADHD*	Control*	D (%)	t-Test†	ANCOVA‡
Total cerebral vol. (mL)	1102 ± 125	1174 ± 107	-6.1	2.98 ( <i>p</i> < 0.01)	—
Cerebellar vol. (mL)	151 ± 13.6	157 ± 11.4	-3.8	1.87 ( <i>p</i> = 0.06)	NS
Vermis vol. (mL)	9.4 ± 1.0	10.3 ± 1.0	-8.5	4.38 ( <i>p</i> < 0.001)	F = 6.30, <i>p</i> = 0.01
Lobules VIII-X vol. (mL)	3.2 ± 0.4	3.6 ± 0.5	-11.7	4.46 ( <i>p</i> < 0.001)	F = 8.20, <i>p</i> < 0.01
Lobules I-V (mm <sup>2</sup> )	481 ± 63	502 ± 57	-4.1	1.66 ( <i>p</i> = 0.1)	NS
Lobules VI-VII (mm <sup>2</sup> )	315 ± 56	309 ± 42	2.0	0.62 ( <i>p</i> = 0.53)	NS
Lobules VIII-X (mm <sup>2</sup> )	328 ± 51	356 ± 51	-8.0	2.67 ( <i>p</i> < 0.01)	F = 4.13, <i>p</i> < 0.05

\* Mean ± SD.

† All *p* values are two-tailed.

‡ ANCOVA with total cerebral volume and WISC-R Vocabulary subtest scores covaried.

ADHD = attention-deficit hyperactivity disorder; D = difference; WISC-R = Wechsler Intelligence Scale for Children-Revised.

correlated significantly with total brain volume ( $r = 0.32$ ,  $p = 0.01$ ), vermal volume ( $r = 0.37$ ,  $p = 0.01$ ), and lobules VIII to X volume ( $r = 0.42$ ,  $p = 0.004$ ) but not with total cerebellar volume ( $r = 0.14$ ,  $p = 0.37$ ). The volumes of the vermis and of lobules VIII to X correlated significantly with right-caudate volume ( $r = 0.39$  and  $r = 0.38$ , respectively,  $p < 0.01$ ). The volumes of the vermis and of lobules VIII to X also correlated significantly with total cerebral volume ( $r = 0.59$  and  $r = 0.62$ , respectively,  $p < 0.0001$ ).

Within the control group, vermis volume correlated significantly with total cerebral volume and left-caudate volume ( $r = 0.34$  and  $r = 0.30$ , respectively,  $p < 0.05$ ). The correlations between vermis volume and total cerebral volume ( $r = 0.62$  in ADHD,  $r = 0.25$  in controls) differed significantly between groups ( $z_r = 2.16$ ,  $p = 0.03$ ).

In a stepwise regression analysis, the volume of lobules VIII to X entered the discriminant function first, with  $R^2 = 0.18$ ; right-globus pallidus volume was second, increasing the cumulative  $R^2$  to 0.27; and caudate asymmetry was third, with cumulative  $R^2 = 0.32$ . These three measures correctly classified (jackknifed analysis) 75.6% of patients with ADHD, 76.6% of controls, and 76.1% of all subjects. Regression analysis limited to noncerebellar measures (total cerebral volume, right- and left-caudate and globus pallidus volumes and asymmetries) was nearly as effective in correctly classifying subjects (overall efficiency 73.9%), but the three measures that contributed significantly (right-globus pallidus, caudate asymmetry, and total cerebral volume) only accounted for 22% of total variance.

**Behavioral data.** None of the boys in the control group had neurologic abnormalities on examination. In the ADHD group, none had ataxia, frank dysmetria, or dysdiadochokinesia, but six had subtle neurologic signs demonstrating some difficulties in coordination: three had poor tandem walk, one had difficulties maintaining stability with eyes closed, two had minimal overflow, one had slight dysmetria on finger-to-nose test, one had difficulties with rapid alternating movements, and two were globally characterized as "clumsy." However, the cerebellar measurements of these six subjects did not differ significantly from those of the remaining patients. Vermal mean volume was  $9.19 \pm 0.67$  versus  $9.43 \pm 0.99$  mL ( $p = 0.46$ ), and posterior-inferior lobe volume was  $3.16 \pm 0.47$  versus  $3.16 \pm 0.42$  mL for the six children with subtle signs versus the remaining ADHD children, respectively. There were no significant correlations between cerebellar measures and Conners Parent or Teacher Ratings of hyperactivity.

**Discussion.** We found that both area and volumetric analyses consistently showed a smaller cerebellar vermis in boys with ADHD, and this reduction seemed to involve particularly lobules VIII to X (figure 2). In contrast to our previous publication,<sup>7</sup> total cerebellar volume was not smaller after correction for total cerebral volume using an improved image quantification analysis in a subsample of right-handed subjects. As in our prior article,<sup>7</sup> total cerebral volume was 6.1% smaller in the ADHD group than in controls, although this difference did not retain significance when Vocabulary IQ scores were covaried ( $p = 0.07$ ). This difference in total cerebral volume, which was also reported in another study,<sup>5</sup>

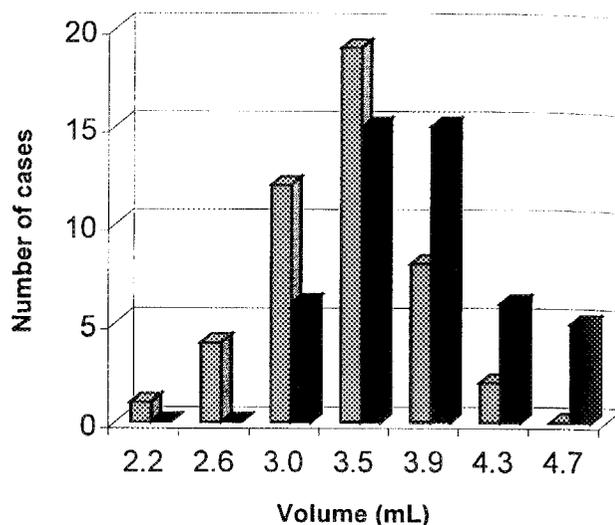


Figure 2. Volumes of vermis lobules VIII through X in 46 right-handed boys with attention-deficit hyperactivity disorder (ADHD) and 47 healthy controls. Shaded bars represent ADHD patients; black bars represent controls.

may be partly explained by the moderately but significantly lower IQ typically found in ADHD groups. Significant positive correlations have been reported between IQ and the volume of the cerebrum as well as the cerebellum.<sup>37</sup> Within our ADHD group, full-scale WISC-R IQ correlated significantly with vermal and total cerebral volumes. Our findings in the vermis, however, did not differ when total cerebral volume and Vocabulary or Block Design subtests were used as covariates. Moreover, differences in the vermis between patients with ADHD and controls cannot be explained by medication history because these findings held for a separate sample of drug-naïve patients (unpublished data).

Previous anatomic studies in ADHD focused on cerebral cortex, particularly the prefrontal region,<sup>4,5</sup> basal ganglia,<sup>10,11</sup> and corpus callosum.<sup>38</sup> Findings of decreased volumes in these structures have supported the hypothesis of an "executive dysfunction" model whose neural substrate would involve frontostriatal circuitry.<sup>3,39</sup> In a previous study of 57 boys with ADHD and 55 healthy controls (which included all the subjects in the present study), we also found a significant reduction in caudate and globus pallidus volumes primarily on the right side.<sup>7</sup>

The cerebellum in contrast has rarely been studied. A CT study using qualitative ratings found "cerebellar atrophy" in 25% of 24 patients with childhood diagnoses of minimal brain dysfunction versus 3.8% of 27 contrast subjects, although the difference was not statistically significant ( $p = 0.1$ ).<sup>27</sup> Despite this scant literature, our findings are supported by a wide range of evidence. "Subtle neurologic signs" can be detected in over 50% of children with ADHD,<sup>40</sup> and similar neurologic symptoms in "clumsy children" have been shown to be associated with either basal ganglia or cerebellar dysfunction (including

dysmetria, dysdiadochokinesia, and intention tremor).<sup>41</sup> Children with learning disabilities and ADHD have also been reported to be impaired in cerebellar-vestibular tests as well as in tests of optokinetic fixation and perceptual span.<sup>42</sup> They also exhibited premature saccades in a delayed oculomotor response task, suggesting a deficit in response inhibition.<sup>43</sup> A recent PET study found that methylphenidate increased cerebellar and decreased basal ganglia metabolism in healthy adults.<sup>44</sup>

Other lesions associated with ADHD may cause cerebellar pathology. In children prenatally exposed to alcohol, deficits in attention and hyperactivity are frequently identified, and abnormal development of the cerebellar vermis with a smaller anterior lobule has been noted.<sup>45</sup> However, fetal alcohol syndrome is also characterized by other characteristics including facial dysmorphia, growth retardation, and neurologic lesions. Moreover, differences in neurocognitive and behavioral measures have been demonstrated in alcohol-affected children compared with those with ADHD.<sup>46</sup> In our study, none of the subjects presented the characteristics of fetal alcohol syndrome, and none of the mothers admitted such a history on structured interview, although we cannot exclude the possibility that excessive alcohol was consumed during pregnancy.

Preclinical studies also support the hypothesis that cerebellar misdevelopment may be associated with learning disabilities and hyperactivity. In rats, the volume of the cerebellar molecular layer correlated with attention to novelty.<sup>47</sup> Moderate cerebellar microneural hypoplasia secondary to chronic irradiation between 8 and 15 postnatal days led to later hyperactivity at an age when animals tend to be most active.<sup>48</sup> Learning deficits and hyperactivity attenuated by stimulants have been reported as a consequence of lead poisoning in animals,<sup>49</sup> with associated vascular abnormalities and hemorrhages found particularly in the cerebellum.<sup>50</sup>

The relationship among the cerebellum, basal ganglia, and prefrontal regions has also been recently studied.<sup>51</sup> The basal ganglia and cerebellum are now known to be connected to areas of the prefrontal cortex involved in cognitive functions, injury to which can lead to executive dysfunction.<sup>16,19</sup> Cerebellar abnormalities also have been reported in autism, obsessive-compulsive disorder, and schizophrenia. In patients with schizophrenia, dysfunction of a prefronto-thalamic-cerebellar circuit has been suggested from a PET study.<sup>52</sup> Using the same methodology, a significant reduction in vermis volume has also been recently detected in childhood-onset schizophrenia.<sup>53</sup> In autism some quantitative MRI and autopsy studies reported abnormalities within the posterior lobe (lobules VI and VII).<sup>54</sup> In the present study, the anterior lobe (lobules I to V) and lobules VIII to X were decreased with sparing of lobules VI and VII. This complementarity is intriguing in light of the embryologic and phylogenetic origins of the vermal lobules. Lobules VI and VII derive from dif-

ferent primordial tissues, and differ in the timing of neurogenesis and migration of Purkinje and granule cells, being the last regions of the vermal cortex to develop.<sup>48</sup> It is also interesting to note that prenatal alcohol exposure in rats has produced Purkinje cell loss in lobules I to V and IX and X but not in lobules VI and VII.<sup>55</sup>

Functional-imaging studies in animals and humans using event-related potentials, PET, or functional MRI have shown changes in cerebellar blood flow in response to different cognitive nonmotor tasks. These changes suggest the cerebellum is involved in the cognitive functions of learning,<sup>21,56</sup> spatial encoding,<sup>23</sup> visual discrimination,<sup>57</sup> and visual attention.<sup>17</sup> Recently, several investigators emphasized the role of the cerebellum in motor and perceptual-timing functions. Cerebellar patients have been found to be impaired in discriminating auditory intervals,<sup>58</sup> in velocity perception,<sup>59</sup> and in perceptual timing.<sup>20</sup> Lesions in hemispheres were attributed to a deficit in a central-timing process, whereas patients with medial lesions had an accurate perception of timing but were unable to implement the response at the desired time.<sup>60</sup> In healthy volunteers, PET activation was shown during an auditory-timing task to be not only in the cerebellar hemispheres but also in the vermis, as well as in thalamus and caudate nuclei. These activations were distinguished from activations due to motor execution.<sup>24</sup> These findings might explain timing-control deficits in clumsy children with cerebellar subtle neurologic signs.<sup>41</sup>

This study has several limitations. As in all brain morphometric studies, both groups exhibited a high degree of variance. ADHD is undoubtedly a heterogeneous disorder, and we did not find a specific subgroup with "cerebellar vermis hypoplasia" but rather a statistically significant reduction relative to a control group. This was demonstrated in the minimal change in classificatory efficiency when cerebellar measures were added to basal ganglia volumes in stepwise regression analysis. Although the percentage of subjects correctly classified barely improved, the percentage of explained variance increased markedly from 22% to 32%. These observations are consistent with the high degree of intercorrelation between vermis and caudate volumes in the ADHD group, and with the salience of the anatomic differences in the vermis.

The most important limitation of this study is the absence of a specific clinical battery including timed responses and quantification of errors to explore subtle neurologic signs.<sup>40</sup> Our standard neurologic examination detected only poor coordination or clumsiness in six boys in the ADHD group. However, vermal volumes for those six subjects did not differ from those for the larger group.

Finally, we cannot specify whether these anatomic reductions might have been a result of differences in the number of cells (neurons or glia) or the number of synapses or whether these neuroanatomic findings

were acquired prenatally or postnatally. Our results do suggest, however, a significant vermal volume reduction in right-handed boys with ADHD.

It has been postulated that the cerebellar vermis, a paleocortical structure, participates in a "lower-level" neural function loop underlying control of movement. The cerebellar hemispheres, on the other hand, being neocortical structures, are thought to be involved in a "cerebello-thalamo-prefrontal reverberating circuit" functioning on a higher level to subserve the planning of movement.<sup>61</sup> However, even if the phylogenetic increase in cerebellar foliation is more pronounced in cerebellar hemispheres than in the vermis, there is a phenomenal increase in the number of folia comparing rat and human vermis.<sup>61</sup> In this study, the cerebellar vermis and posterior inferior lobe volumes were found to be reduced in ADHD boys, whereas cerebellar total volume, which is largely composed of the cerebellar hemisphere volumes, was less reduced in proportion to total brain volume differences. The finding of differences in the vermis rather than in the hemispheres might indicate that in ADHD and in childhood-onset schizophrenia<sup>53</sup> the cerebellum is implicated in motor control dysfunctions such as neurologic subtle signs or deficits in motor inhibition (responsible for clumsiness and poor coordination), rather than having a primary role in cognitive functions. However, connections with prefrontal associative areas also suggest that the vermis may act as a coprocessor, enhancing speed and efficiency in attention and executive functions.<sup>62</sup> Increases in vermal blood flow during a shifting attention task have been found in a human fMRI study,<sup>63</sup> and patients with cerebellar lesions have been shown to have shifting attention deficits.<sup>17</sup> It has been suggested that part of the cognitive deficits in cerebellar patients might be described as deficits in executive function because impairments are seen only in tasks such as the initiation-perseveration subtest of the Mattis Dementia Rating Scale and fluency tests and in memory measures requiring a greater processing effort.<sup>6</sup>

In conclusion, the current study supports the involvement of the cerebellar vermis in ADHD. Although the contribution of the cerebellum to cognition remains unclear and somewhat controversial, converging human and animal data suggest that dysfunctions in cerebello-thalamo-prefrontal circuitry underlying connections between cerebellum and prefrontal associative areas might subservise at least some of symptoms encountered in ADHD. Future functional imaging studies of ADHD should focus on patterns of cerebellar activation during response inhibition and other executive function tasks.

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