Developmental Equations Reflect Brain Dysfunctions

Abstract. *Developmental equations, which predict 32 parameters of the electroencephalogram recorded from the healthy human as a function of age, were tested in diverse groups of children. Few significant deviations were found in normal children, even in a culture different from the one on which the equations were based. A high incidence of significant deviations was found in children with learning disabilities and those at risk for various neurological disorders.*

We described previously (*1*) the construction of a set of developmental equations that predict the distribution of the relative (percentage) power in the delta, theta, alpha, and beta bands of frontotemporal, temporal, central, and parietooccipital derivations in the resting (eyes closed) electroencephalograms (EEG's) of children as a function of their age (*2*). These neurometric equations predict the values of 32 EEG parameters extracted from a 60-second EEG sample. Extensive studies of different groups of normal children showed uniformly good correspondence to the predicted values. Using these neurometric equations we have obtained data that confirm the low incidence of false positive findings in a group of normal children from a different culture and demonstrate significant deviations from the predicted values in children "at risk" for a variety of brain dysfunctions or with learning disabilities.

The data presented here were gathered by automatic data acquisition terminals controlled by a microprocessor that performed on-line rejection of artifacts and recorded all data on floppy disks (*3–5*). The acquisition terminals were placed at six sites: our laboratories at the New York University (NYU) Medical Center; a suburban school in Suffolk County, New York (*6*); a pediatric neurology service in Philadelphia (*7*); the National Nutrition Centre in Barbados (*8*); a mental health facility in Westchester, New York (*9*); and a rural area of Maryland (*10*). Disks recorded by all six terminals were sent to the computer center of the Brain Research Laboratories at NYU Medical Center for analysis. The first step in processing was to generate a paper record of the EEG. These tracings were examined visually for artifacts that eluded the computer rejection algorithm, and all segments considered to be contaminated were edited out of the record. These artifact-free EEG samples, usually totaling 40 to 50 seconds out of the original 60 seconds, were subjected to digital filtering to extract the absolute power in the four frequency bands from the four derivations on each side of the head. These absolute power measures were then converted to relative power, log-transformed [log $(x/100 - x)$], and subjected to Z transformations relative to the means and standard deviations generated by the neurometric equations appropriate to the age of the subject. The resulting Z values can be used to estimate the probability that such values would be obtained by chance from the same derivation in a healthy individual of the same age (*1*). Any Z values greater than or equal to 1.64 ($P \leq .05$) are considered deviant or to be a "hit."

In a preliminary validation period, disks recorded from normal children and from patients with known neurological diseases, as well as repeated disks from the same patient, were sent from St. Christopher's Hospital in Philadelphia to the Brain Research Laboratories for blind analysis. After this period, which confirmed the low incidence of false positive results in the normal controls and the high incidence of abnormal findings in patients, the present study was started. Differences that might be attributed to the use of different acquisition systems were tested for in samples of normal children gathered from all six sites. No significant differences were found in the distribution of Z values for the 32 EEG parameters, with respect to acquisition terminals, date of test, and age of child.

Data were gathered from an extensive sample of normal children (*8–11*), children at risk for neurological disorders (*7*), and children with learning disabilities (*12*). These samples were divided into five groups: group 1 (U.S. norms), 306 children, 6 to 16 years old of normal intelligence and school achieve-

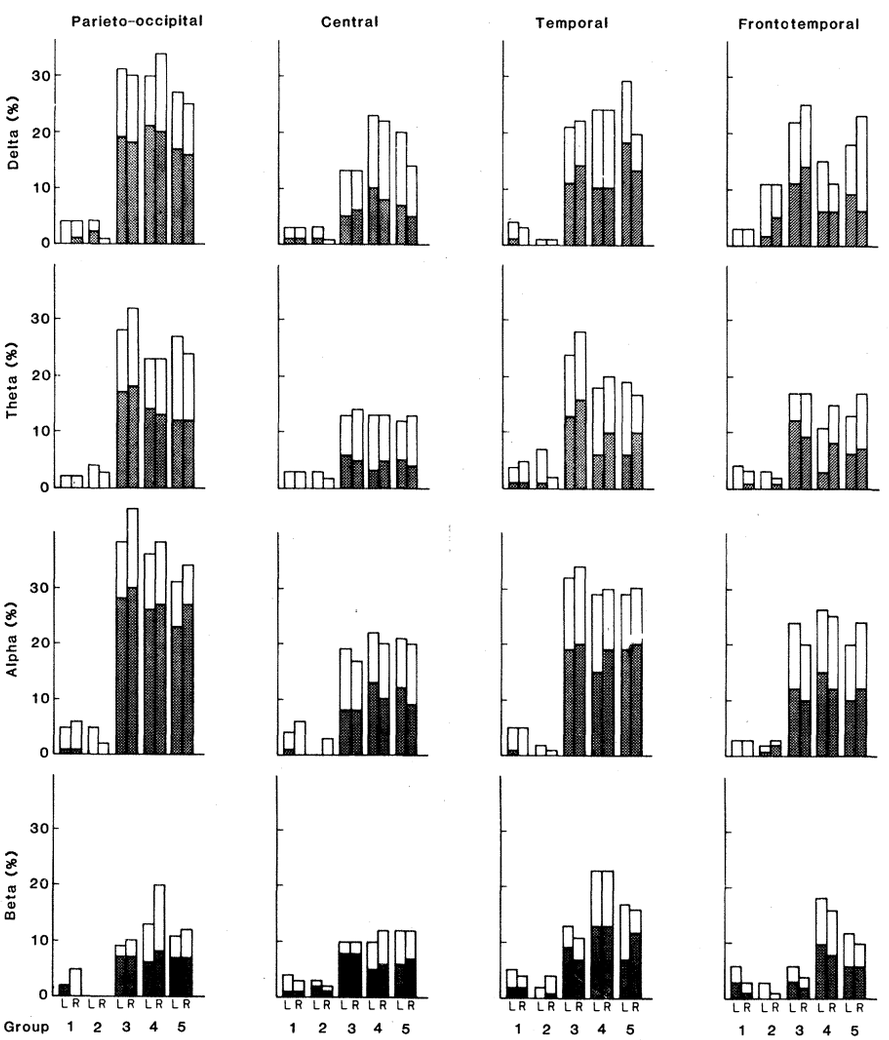

Fig. 1. Percentage distribution of hits for the five groups. Height of bars corresponds to hits at the $P \leq .05$ level; shaded portion corresponds to hits at the $P \leq .01$ level.

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ment; group 2 (Barbados normals), 91 children, 5 to 12 years old, of normal intelligence and school achievement; group 3 (neurological), 474 patients, 6 to 16 years old, considered at risk for neurological disorders and examined in a pediatric neurology service; group 4 (learning disabled), 143 children, 6 to 16 years old, of borderline normal intelligence who had exhibited generalized learning disabilities and poor achievement in one or more areas; and group 5 (specific learning disabled), 163 children, 6 to 16 years old, of normal intelligence who had exhibited specific learning difficulties with poor achievement in at least one area (*13, 14*).

The neurometric developmental equations were based on data gathered from the 306 normal U.S. children in group 1, and all individual data were Z-transformed relative to these predicted normal values. For each group, Table 1 presents the percentage of findings that were within normal limits and those that were deviant. The significance of differences in the distribution of Z values between group 1 and each of the other groups was tested by computing the value of χ^2 on the actual distributions for every measure. Because of the large number of comparisons, conservative significance levels were used based on exact probabilities of the χ^2 distributions (*15, 16*).

Table 1 shows that for group 1 the Z values for the relative power in all frequency bands in all derivations conformed closely to the expected distributions. No single measure deviated from the mean (at $P \leq .05$) by more than 6 percent. Similarly, the percentage of "hits" ($P \leq .05$) for the 32 individual measures in group 2 was low, ranging from 0 to 12 percent. Further, Table 2 shows that for 31 of the 32 EEG measures there were no significant differences between the distributions of deviant Z values in normal children from the United States (group 1) and Barbados (group 2). These findings reconfirm the accuracy of the predicted values calculated from the neurometric equations, and establish that the predicted EEG values from the neurometric normative data base are applicable to children who live in predominantly rural areas of the Caribbean and whose cultural environment is markedly different from that of U.S. children.

In contrast, the neurological subjects (group 3) and both groups of learning disabled children (groups 4 and 5) showed a marked incidence of deviant Z values for individual measures, ranging from 4 to 44 percent. In fact, in 84 of

Table 1. Percentage distribution of Z-transformed EEG measures for five groups. N is the number of subjects. We classified a child as dysfunctional if we found more than twice the number of significant values that would be expected by chance. By this criterion, at the $P \leq .05$ level, 10 percent of group 1, 6.9 percent of group 2, 58 percent of group 3, 57 percent of group 4, and 54 percent of group 5 would be classified as dysfunctional. At the $P \leq .01$ level, 4 percent of group 1, 2 percent of group 2, 48 percent of group 3, 46 percent of group 4, and 47 percent of group 5 would be considered dysfunctional. Abbreviations: L, left; R, right; PO, parieto-occipital; C, central; T and FT, temporal and frontotemporal, respectively; and N.S., not significant.

Derivation	Group 1, U.S. normals (N = 306)			Group 2, Barbados normals (N = 91)			Group 3, Neurological "at risk" (N = 474)			Group 4, Learning disabled (N = 143)			Group 5, Specific learning disabled (N = 163)		
	N.S.	$P \leq .05$	$P \leq .01$	N.S.	$P \leq .05$	$P \leq .01$	N.S.	$P \leq .05$	$P \leq .01$	N.S.	$P \leq .05$	$P \leq .01$	N.S.	$P \leq .05$	$P \leq .01$
Delta															
LPO	96	4	0	96	4	2	69	31	19	70	30	21	73	27	17
RPO	96	4	1	99	1	0	70	30	18	66	34	20	75	25	16
LC	97	3	1	97	3	1	87	13	5	77	23	10	80	20	7
RC	97	3	1	99	1	0	87	13	6	78	22	8	86	14	5
LT	96	4	1	99	1	0	79	21	11	76	24	10	71	29	18
RT	97	3	0	99	1	0	78	22	14	76	24	10	80	20	13
LFT	97	3	0	89	11	2	78	22	11	85	15	6	82	18	9
RFT	97	3	0	88	12	5	75	25	14	89	11	6	77	23	6
Theta															
LPO	98	2	0	96	4	0	72	28	17	77	23	14	73	27	12
RPO	98	2	0	97	3	0	68	32	18	77	23	13	76	24	12
LC	97	3	0	97	3	0	87	13	6	87	13	3	88	12	5
RC	97	3	0	98	2	0	86	14	5	87	13	5	87	13	4
LT	96	4	1	93	7	1	76	24	13	82	18	6	81	19	6
RT	95	5	1	98	2	0	72	28	16	80	20	10	83	17	10
LFT	96	4	0	97	3	0	83	17	12	89	11	3	87	13	6
RFT	97	3	1	98	2	1	83	17	9	85	15	8	83	17	7
Alpha															
LPO	95	5	1	95	5	0	62	38	28	64	36	26	69	31	23
RPO	94	6	1	98	2	0	56	44	31	62	38	27	66	34	21
LC	96	4	1	100	0	0	81	19	8	78	22	13	79	21	12
RC	94	6	0	97	3	0	83	17	8	80	20	10	80	20	9
LT	95	5	1	98	2	0	68	32	19	71	29	15	71	29	19
RT	95	5	0	99	1	0	66	34	20	70	30	19	70	30	20
LFT	97	3	0	98	2	1	76	24	12	74	26	15	80	20	10
RFT	97	3	0	97	3	2	80	20	10	75	25	12	76	24	12
Beta															
LPO	98	2	2	100	0	0	91	9	7	87	13	6	89	11	7
RPO	96	4	2	100	0	0	90	10	7	80	20	8	88	12	7
LC	96	4	1	97	3	2	90	10	8	90	10	5	88	12	6
RC	97	3	1	98	2	1	90	10	8	88	12	6	88	12	7
LT	95	5	2	98	2	0	87	13	9	77	23	13	83	17	7
RT	96	4	2	96	4	1	89	11	7	77	23	13	84	16	12
LFT	94	6	3	97	3	0	94	6	3	82	18	10	88	12	6
RFT	97	3	1	99	1	0	96	4	2	84	16	8	90	10	6

the 96 individual measures (88 percent), the percentage of hits in groups 3, 4, and 5 was greater than the highest single value (12 percent) obtained in the two normal groups (see Fig. 1). Excess slow waves (delta plus theta) in the parieto-occipital regions were far more frequent than any other frequency or regional abnormality. Central slow-wave hits were comparatively few relative to parieto-occipital and temporal regions. On the basis of relative power, significantly deficient alpha waves in groups 3, 4, and 5 may be considered as only a by-product of excess slow waves.

Hits at the $P \leq .05$ level were significant in 29 out of the 32 comparisons in group 3, 29 out of 32 comparisons in group 4, and 28 out of 32 comparisons in group 5. Hits at the $P \leq .01$ level in group 3 were again significant for 30 out of 32 comparisons and in group 4 for 25 out of 32 comparisons. Hits in group 5 at $P \leq .01$ drop to 22 out of 32 measures, no longer showing significant differences from group 1 for right central slow waves. Table 2 shows that most of the significant values were beyond the $P \leq .0001$ level. Significant hits were diffusely distributed over all head regions for the delta, theta, and alpha bands. This diffuse distribution of hits in all three groups (groups 3, 4, and 5) suggests that dysfunction in any cerebral region can contribute to a wide variety of performance or behavioral deficiencies.

Since false positive conclusions about brain dysfunction can have far-reaching consequences we considered it desirable to define the threshold for inferring probable dysfunction as approximately twice the number of significant values expected by chance, that is, four values at $P \leq .05$ or two values at $P \leq .01$. Using this criterion we found that the overall incidence of false positives in group 1 was 10 percent ($P \leq .05$). In group 2 (Barbados normals) the overall incidence of false positives was 9 percent. This finding replicates the low incidence of false positives obtained when we used an independent sample of normal healthy children from a different culture. Thus, the false positives obtained in two independent samples of normal children by using neurometric equations compares favorably with the 12 to 30 percent incidence of false positives reported in normals when conventional visual methods of EEG analysis were used (*17, 18*).

With respect to the ability of the equations to identify true positives, the overall incidence of children with twice the number of hits expected by chance at $P \leq .05$ was 58 percent in group 3, 57 percent in group 4, and 54 percent in group 5. If we change the threshold to one in which we consider only cases with twice the number of hits expected by chance at the $P \leq .01$ level, the false positive rate is reduced to 4 percent in group 1 and 2 percent in group 2, whereas 48 percent in group 3, 46 percent in group 4, and 47 percent in group 5 are still considered to be dysfunctional (true positive).

In computing the percentage of hits for each of the 32 measures, an individual child might show a hit on every measure. In computing the overall percentage of children whose hits exceed threshold, an individual child is only counted once. In groups 3, 4, and 5 the overall percentage of children exceeding the threshold was higher than the highest percentage of hits on any measure and more than doubled the average percentage of hits across all measures (Table 1) (*19*). This shows that different children were deviant in different measures and implies the existence of different homogeneous subgroups, with distinct profiles of neurometric deviations (which may correlate with different behavioral deficits) within the heterogeneous population subsumed by the label for each of these groups, as we have shown elsewhere (*4, 20*).

Our data thus demonstrate that the neurometric developmental equations, previously shown to be stable both within and across cultures, yield few hits in normal healthy children and detect a substantial incidence of significant deviations from normal values in heterogeneous groups of children at risk for a wide variety of neurological diseases or learning disabilities.

Measurement of these EEG parameters may offer a brief, reliable, and economic method for rapid examination of children who, because of consistent behavioral problems or learning difficulties, are considered at risk for brain

Table 2. Significant differences in the frequency distribution of hits. The U.S. norms (group 1) are compared to Barbados normals (group 2), neurological subjects (group 3), learning disabled subjects (group 4), and specific learning disabled subjects (group 5) by χ^2 analysis. The significance levels are based on exact probabilities of χ^2 distributions (*15*).

Derivation	Group 1 versus 2		Group 1 versus 3		Group 1 versus 4		Group 1 versus 5	
	$P \leq .05$	$P \leq .01$	$P \leq .05$	$P \leq .01$	$P \leq .05$	$P \leq .01$	$P \leq .05$	$P \leq .01$
Delta								
LPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
RPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
LC	N.S.	N.S.	.001	.01	.0001	.001	.0001	.01
RC	N.S.	N.S.	.0001	.01	.0001	.05	.001	N.S.
LT	N.S.	N.S.	.0001	.0001	.0001	.01	.0001	.0001
RT	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
LFT	N.S.	N.S.	.0001	.0001	.01	.05	.0001	.0001
RFT	.05	.05	.0001	.0001	N.S.	.05	.0001	.01
Theta								
LPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
RPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
LC	N.S.	N.S.	.0001	.001	.05	.05	.01	.05
RC	N.S.	N.S.	.0001	.01	.01	.05	.01	N.S.
LT	N.S.	N.S.	.0001	.0001	.0001	N.S.	.0001	N.S.
RT	N.S.	N.S.	.0001	.0001	.001	.01	.001	.001
LFT	N.S.	N.S.	.0001	.0001	N.S.	N.S.	.05	.01
RFT	N.S.	N.S.	.0001	.0001	.001	.01	.0001	.05
Alpha								
LPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
RPO	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
LC	N.S.	N.S.	.0001	.001	.0001	.0001	.0001	.0001
RC	N.S.	N.S.	.001	.001	.001	.0001	.001	.001
LT	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
RT	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
LFT	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
RFT	N.S.	N.S.	.0001	.0001	.0001	.0001	.0001	.0001
Beta								
LPO	N.S.	N.S.	.05	.05	.01	N.S.	.01	N.S.
RPO	N.S.	N.S.	.05	.05	.0001	N.S.	N.S.	N.S.
LC	N.S.	N.S.	N.S.	.001	N.S.	N.S.	N.S.	N.S.
RC	N.S.	N.S.	.05	.05	.05	N.S.	.05	N.S.
LT	N.S.	N.S.	.01	.05	.0001	.0001	.01	N.S.
RT	N.S.	N.S.	.05	.05	.0001	.001	.001	.001
LFT	N.S.	N.S.	N.S.	N.S.	.01	.05	N.S.	N.S.
RFT	N.S.	N.S.	N.S.	N.S.	.001	N.S.	N.S.	N.S.

dysfunction or disorder. While negative findings in such examinations of children with behavioral or learning problems must be considered tentative and inconclusive, positive findings would justify referral for more exhaustive evaluations.

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References and Notes

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2. The equations are first-order functions whose coefficients are published in (*1*). Frequency bands were defined as delta (1.5 to 3.5 Hz), theta (3.5 to 7.5 Hz), alpha (7.5 to 12.5 Hz), and beta (12.5 to 25 Hz). The derivations were F_7T_3, F_8T_4, T_3T_5, T_4T_6, C_3C_z, C_4C_z, P_3O_1, and P_4O_2, according to the nomenclature of the international 10/20 system.
3. These terminals correspond to that described in (*4, 5*), but we used an LSI-11 microprocessor instead of a PDP 11/10 and recorded digital data on floppy disks instead of magnetic tape. Frequency and amplitude calibration signals were recorded regularly to guarantee standardized recording conditions.
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6. Board of Cooperative Educational Services (BOCES) District III, James E. Allen Learning Center, Dix Hills, N.Y.
7. Pediatric Neurology Service, Handicapped Children's Unit, St. Christopher's Hospital for Children, Philadelphia. Supported in part by NIH general CRC grant RR-75. Disks from the neurometric examinations of 474 neurological patients referred to this service were sent to NYU for analysis with no information other than the age of the patient. This terminal was constructed by Neurometrics, Inc., under license from NYU.
8. This terminal was used to gather data on a sample of 129 children who were exposed to malnutrition in the first year of life. They were matched by age, grade, gender, and handedness to a control sample of 129 children who had not suffered from malnutrition. The study (manuscript in preparation) was conducted in collaboration with F. Ramsey, J. Galler, and G. Solimano and was supported by the Ford Foundation, grant 770-0471. The analyses reported here refer only to a subset of the control population (see group 2, Barbados normals).
9. Data gathered at the Rockland Psychological and Educational Center in Spring Valley, N.Y.
10. Data gathered at the Applied Neuroscience Institute, University of Maryland, Eastern Shore, Princess Anne.
11. The normal children examined at BOCES (*6*) and at NYU were studied in a project supported by National Science Foundation grant DAR 78-18772, formerly APR 76-24662, intended to provide part of the data base for construction of an EEG/evoked response discriminant function capable of separating learning disabled from normal children.
12. The learning disabled children were examined in a project cited in (*11*) and in a project supported by the Office of Education, Bureau of Education for the Handicapped (grant G007604516), in which neurometric methods are used to diagnose and help remediation of the learning disabled child.
13. All U.S. normal children (group 1) had scores of 90 or higher on the Peabody Picture Vocabulary Test (PPVT) and standard scores of 90 or higher on all sections (reading, spelling, and arithmetic) of the Wide Range Achievement Test (WRAT). The Barbados normal children (group 2) were the subset of the control group (*8*) which had full-scale Wechsler Intelligence Scale for Children (WISC) scores of 85 or higher and appropriate grade level for age. The WISC was modified by J. Galler to make it culturally relevant for Barbadian children. The learning disabled children (group 4) had IQ scores between 65 and 84 on the WISC-R and WRAT standard scores below 90 in language or arithmetic skills, or both. The specific learning disabled children (group 5) had IQ scores above 85 on the WISC-R, and WRAT standard scores below 90 in language and or arithmetic skills. In groups 4 and 5, PPVT scores were used when WISC-R scores were not available. Most of the children in groups 4 and 5 were attending a special school (*6*) for children unable to learn satisfactorily in their local schools.
14. With the exception of a few children in group 3 with convulsive disorders, none of the children in any group received medication for at least 72 hours prior to examination.
15. On the basis of relative power, one of four frequency bands is a linear combination of the others. Thus, using exact probabilities of χ^2 distributions, we calculated Bonferroni significance levels (*16*) based on 24 independent measures. The critical levels of exact probabilities corresponding to nominal P values ranging from $P \leq .05$ to $P \leq .0001$ were as follows: $P \leq .05$ = 2E-3; $P \leq .01$ = 4E-4; $P \leq .001$ = 4E-5; and $P \leq .0001$ = 4E-6.
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19. The percentage of hits for each of the 32 measures was averaged. The mean percentage of individual hits was 20, 21, and 20 percent at the $P \leq .05$ level and 12, 11, and 10 percent at the $P \leq .01$ level for groups 3, 4, and 5, respectively.
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17 September 1979; revised 28 August 1980

Sex Differences in Mathematical Ability: Fact or Artifact?

Abstract. *A substantial sex difference in mathematical reasoning ability (score on the mathematics test of the Scholastic Aptitude Test) in favor of boys was found in a study of 9927 intellectually gifted junior high school students. Our data contradict the hypothesis that differential course-taking accounts for observed sex differences in mathematical ability, but support the hypothesis that these differences are somewhat increased by environmental influences.*

Huge sex differences have been reported in mathematical aptitude and achievement (*1*). In junior high school, this sex difference is quite obvious: girls excel in computation, while boys excel on tasks requiring mathematical reasoning ability (*1*). Some investigators believe that differential course-taking gives rise to the apparently inferior mathematical reasoning ability of girls (*2*). One alternative, however, could be that less well-developed mathematical reasoning ability contributes to girls' taking fewer mathematics courses and achieving less than boys.

We now present extensive data collected by the Study of Mathematically Precocious Youth (SMPY) for the past 8 years to examine mathematical aptitude in approximately 10,000 males and females prior to the onset of differential course-taking. These data show that large sex differences in mathematical aptitude are observed in boys and girls with essentially identical formal educational experiences.

Six separate SMPY talent searches were conducted (*3*). In the first three searches, 7th and 8th graders, as well as accelerated 9th and 10th graders, were eligible; for the last three, only 7th graders and accelerated students of 7th grade age were eligible. In addition, in the 1976, 1978, and 1979 searches, the students had also to be in the upper 3 percent in mathematical ability as judged by a standardized achievement test, in 1972 in the upper 5 percent, and in 1973 and 1974 in the upper 2 percent. Thus, both male and female talent-search participants were selected by equal criteria for high mathematical ability before entering. Girls constituted 43 percent of the participants in these searches.

As part of each talent search the students took both parts of the College Board's Scholastic Aptitude Test (SAT)—the mathematics (SAT-M) and the verbal (SAT-V) tests (*4*). The SAT is designed for able juniors and seniors in high school, who are an average of 4 to 5 years older than the students in the talent searches. The mathematical section is particularly designed to measure mathematical reasoning ability (*5*). For this reason, scores on the SAT-M achieved by 7th and 8th graders provided an excellent opportunity to test the Fennema and Sherman differential course-taking hypothesis (*2*), since until then all students had received essentially identical formal instruction in mathematics (*6*). If their hypothesis is correct, little difference in mathematical aptitude should be seen between able boys and girls in our talent searches.

Results from the six talent searches are shown in Table 1. Most students

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