DEVELOPMENTAL DYSCALCULIA AND BRAIN LATERALITY*

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ABSTRACT

The correlation between arithmetic dysfunction and brain laterality was studied in 25 children with developmental dyscalculia (DD). The children were tested on a standardized arithmetic battery and underwent a neurological and neuro-psychological evaluation. A diagnosis of left hemisphere dysfunction (n=13) was based on right side soft neurological signs, performance IQ (PIQ)>verbal IQ (VIQ), dyslexia and intact visuo-spatial functions. The criteria for right hemisphere dysfunction (n=12) were left body signs, VIQ>PIQ, impaired visuo-spatial functions and normal language skills. The groups were similar for age, gender, and socio-economic status. Our results showed that both groups scored more than 2 SD below the mean adjusted score on the arithmetic battery, but the left group was significantly worse in 3 areas: mastery of addition/subtraction, complex multiplication and division and visuo-spatial errors (p<0.05). The data indicate that dysfunction of either hemisphere hampers arithmetic acquisition, but arithmetic impairment is more profound with left hemisphere dysfunction.

INTRODUCTION

Developmental dyscalculia (DD) is a primary cognitive disorder affecting the ability of an otherwise normal child to learn arithmetic (American Psychiatric Association, 1987). Even though brain lesions acquired later in childhood or adult life are known to cause dyscalculia (Ashcraft, Yamshita and Aram, 1992; Hécaen, 1976, 1983; Grafman, Passafiume, Faglioni et al., 1982), the issue of how DD is related to brain dysfunction is still a matter of controversy. Some authors suggest an organic pathogenesis for DD (Kosc, 1974; Rourke and Fisk, 1988), while others believe that its etiology is related to reduced intelligence or to the psycho-social context of the child’s environment (Broman, Bien and Shaughness, 1985).

Acquired dyscalculia in adults has been subdivided by Hécaen, Angleругues and Houilliers (1961) on the basis of the neurobehavioral deficit and associated anatomical lesion. According to this classification, three types of acquired dyscalculia are recognized: (1) aphasis dyscalculia, appearing in the wake of lesions in the left hemisphere; (2) visuo-spatial dyscalculia, due to right hemisphere lesions; and (3) anarithmetia, due to left or bilateral lesions. Although


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no clear neuroanatommical correlates are available in children with DD, one of
the classifications of DD, extrapolated from that for adults, subdivides DD
children into 5 groups (Badan, 1983). The first three subgroups are identical
to the original classification of Hecaen et al. (1961), and the other two are
attentional-sequential dyscalculia and mixed type. Another classification for DD
is derived from associated learning disabilities and presumed hemispheric
dysfunction determined by the neuropsychological profile (Rourke, 1993).
Although both classifications are based on neuropsychological features and
presumed hemispheric processing, data correlating neuropsychological function
and arithmetic error types is available only for the latter. Children with associated
reading disorders were characterized by “mechanical” arithmetic errors; children
with nonverbal learning disabilities had more severe mechanical arithmetic errors
as well as problems with the spatial organization of numbers, misreading the
signs, making procedural errors or having difficulty shifting set, and were
deficient in the graphomotor aspects of writing numbers (Rourke, 1993).

We hypothesized that if this or any of the classifications is to be considered
valid, the neuro-psychological features should be reflected in the types of
arithmetic difficulties displayed. To test this supposition we evaluated
hemispheric dysfunction in children with DD and its correlation with the types
of arithmetic errors.

**ARITHMETIC ASSESSMENT**

To study arithmetic knowledge, we developed an arithmetic battery based
on a model of arithmetic processing and calculation developed by McCloskey,
Caramazza and Basili (1985). Their neurocognitive model emphasizes the
different numerical processes in terms of 3 basic subskills: number
comprehension, number production and calculation processing. The
comprehension category includes comprehension of quantities, the symbolic
nature of numbers (lexical processing) and digit order (syntactic processing).
The number production subsystems are counting, reading and writing numbers.
Calculation processing is subdivided into comprehending operation symbols,
executing arithmetic exercises and memorizing numerical facts. Their model taps
many of the developmental aspects of arithmetic acquisition in preschool children
as delineated by Gelman and Gallistel (1986) and Siegler and Robinson (1982).
Preschool children acquire concepts of counting, magnitude, and number
conservation. Acquisition of one subskill enables the child to understand other
arithmetic tasks. For example, the act of learning to count enables the child to
develop representations of numerosity, conservation of numbers, reasoning
principles, the ability to do operations (addition, subtraction, multiplication and
division) and to develop abstract principles of numerical reasoning as in algebraic
exercises (Gelman and Gallistel, 1986). According to Siegler and Robinson
(1982), it is possible to analyze a child’s understanding of number concepts by
breaking down the arithmetic skills involved.

Since the model of McCloskey et al. (1985) appears to parallel in many
ways the developmental phases in arithmetic acquisition as delineated by Gelman
and Gallistel (1986) and Siegler and Robinson (1982) (Geary, 1993), we
assembled an arithmetic battery designed to test basic number knowledge as
outlined by the model. The battery taps knowledge of arithmetic calculation
processes, number facts, comprehension of number quantities, counting, number
concepts and operation symbols. These subtests were devised to sample each
area of the McCloskey et al. model (number comprehension, number production,
and number calculation) and were standardized on a representative sample of
elementary school; the details of the test have been published elsewhere (Shalev,
Manor and Gross-Tsur, 1993). Errors were evaluated and categorized
quantitatively and qualitatively: total number of mistakes on the arithmetic
battery, errors in complex addition and subtraction and multiplication and
division, errors in number comprehension, number production, number facts and
calculation. Attentional errors noted were inattention to the operation sign, usage
of the wrong sign, and forgetting to carry over; errors considered to be visuo­
spatial were misplacement of digits, rotations, and undertaking the exercise in
the wrong direction. Dysphasic errors were misnaming of numbers or writing
the wrong name of a number otherwise correctly identified. Total time of test
was also measured. Indices relating the number of errors to the number of
exercises attempted was developed to control for the differences among children
approaching different numbers of exercises. After reviewing each test
individually, an evaluation of the child’s mastery of the principles of addition/
subtraction and multiplication/division was made. The test was scored by an
independent observer unaware of the child’s clinical diagnosis. The scores on
this normal sample were obtained for use as a standard of comparison for studies
of children with DD.

MATERIALS AND METHODS

Subjects

Children referred were those estimated by their teachers to be seriously impaired in
arithmetic (i.e. at least 2 years below grade level). They underwent a modified neurological
examination as per Touwen and Prechtl (1970); EEG, brain CT (when indicated); the
arithmetic battery and psychological battery which included the WISC-R; Raven’s colored
progressive matrices (Raven, 1965); Rey-Osterreith complex figure (Osterreith, 1944); reading
and writing of age appropriate material provided by the Ministry of Education (standardized
tests are not available in Israel); Conners abbreviated questionnaire (parent/teacher) (Conners,
1973). Socio-economic status was determined according to father’s profession (Abramson et
al., 1983).

Criteria for inclusion were normal perinatal history and neurological development, intact
hearing and vision and attendance in a regular school. Exclusion criteria were seizure
disorders, or any specific psychiatric disorders or drug medication with the exception of
ritalin. A diagnosis of attention deficit hyperactivity disorder (ADHD) was based on clinical
criteria as per the DSM-III-R and a score of ≥15 on the Conners’ questionnaire.

According to the results of this evaluation, children with neurological/neuro-psychological
findings associated with left or right hemispheric dysfunction were included in the study
(Tables I and II). Children with signs of bilateral hemispheric dysfunction, with no specific
hemispheric signs and children with Gerstmann’s syndrome were excluded. Neurological
lateralizing signs were determined if on the modified neurological assessment, as specified
by Touwen and Prechtl, there were a combination of neurological signs which formed a
specific unilateral pattern: a combination of slightly increased (or decreased) tendon reflexes, slightly increased resistance to passive movement, dorsiflexion of the big toe and/or some pronation of one of the extended arm, all on the same side of the body (Touwen and Prechtl, 1970). A presumptive diagnosis of left hemisphere dysfunction was made if there were a combination of right body signs, abnormal language related tasks such as dyslexia, performance IQ (PIQ)>verbal IQ (VIQ) and normal visuo-spatial functions (Table III). The diagnosis of right hemisphere dysfunction was made if there were left body lateralizing signs, VIQ>PIQ, impaired visuo-spatial functions and normal verbal and language tasks (Table IV). The decision of hemisphere laterality was made by 3 observers (RSS, VGT, RWE). After an initial discussion of criteria, the observers independently determined the diagnosis and agreement was achieved in all but 2 of the cases (estimated kappa of agreement was =0.91). We then correlated the neurological profile of the children with the arithmetic error type.
### TABLE III
Results of Psychological Tests for 13 Children with Left Hemisphere Dysfunction

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Mean: 95.4, S.D.: 11.0

VIQ = Verbal IQ; PIQ = Performance IQ; Inf = Information; Sim = Similarities; Voc = Vocabulary; Arith = Arithmetic; DS = Digit span; Read = Reading evaluation (-1, -2 years below expected grade); Writ = Writing evaluation (-1, -2 years below expected grade); R-O = Rey-Osterreith complex figure (percentiles); Mem = Memory; CPM = Coloured progressive matrices; PA = Picture arrangement.

### TABLE IV
Results of Psychological Tests for 12 Children with Right Hemisphere Dysfunction

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Mean: 101.4, S.D.: 11.5

VIQ = Verbal IQ; PIQ = Performance IQ; Inf = Information; Sim = Similarities; Voc = Vocabulary; Arith = Arithmetic; Cod = Coding; Read = Reading evaluation (-1, -2 years below expected grade); Writ = Writing evaluation (-1, -2 years below expected grade); R-O = Rey-Osterreith complex figure (percentiles); Mem = Memory; CPM = Coloured progressive matrices; DS = Digit span; PA = Picture arrangement.

### Statistical Analysis

The t-test was used for comparisons of the age standardized scores on the arithmetic battery, both for the total score and scores of the sub-tests. Comparison of the indices for specific types of errors were carried out using ANCOVA (analysis of covariance) thus enabling adjustment for grade and IQ effect. (Although the groups did not differ significantly with respect to the mean age, the analyses were carried out while adjusting for grade because...
of the strong association between school class and performance). The various measures of each type of error were dichotomized into either high number of errors or low number of errors. The chi-square test (or Fisher exact test) were used to compare the 2 groups with respect to the dichotomized variables. The Mantel Hanszel test was used for comparison after adjusting for IQ and grade effect and Mantel Hanszel odds ratio was used for a grade adjusted comparison between the study group and a group of normal children (Fleiss, 1981).

**RESULTS**

There were 13 children with a left hemisphere dysfunction, and 12 with right hemisphere dysfunction (Tables I and II). There were 15 boys and 10 girls, whose mean age in years was 11.1 (S.D. = ±2.2); 7 were left handed. There were more left handed children in the left group (n = 5) than the right (n = 2), probably reflecting another manifestation of left hemisphere dysfunction. There was no significant differences with respect to gender, presence of ADHD, or socioeconomic status between the 2 groups. Although there were no significant differences with respect to age, there was a difference of one school grade, requiring analyses be adjusted for class effect. The mean full scale IQ was 103±11 for the left group and 92±12 for the right group (p<0.05), verbal IQ 95 and 101 (p = NS), and performance IQ 110 and 84 (p<0.01) respectively. The score on the WISC-R arithmetic subtest was 6.0±2.0 for the left hemisphere group and 6.8±3.3 for the right group (p = NS).

The performance of the children on the standardized arithmetic battery was as follows. The study group demonstrated weakness in all 3 areas of the battery compared to age matched normal children (Shalev et al., 1993). The mean z-scores on the entire arithmetic battery was −3.5±2.1 for both hemispheric groups, indicating that their overall performance on arithmetic was extremely poor, i.e. over 2 SD from the mean for their grade. Their weaknesses were more marked in the areas of number facts and complex calculation, with relative sparing of function in the domains of number production and comprehension. For number comprehension their odds for making 2 or more errors was equal to that of the normal children. For number production the respective odds ratio was 2.26, which was not significant. This is in contrast to the odds for calculation errors. The odds of the study group for making 2 or more errors in simple addition, subtraction, multiplication and division were respectively 4.76, 4.37, 16.67, and 7.14 times that of the normal children. All these odds ratio were significant (p<0.05). For complex calculation, all but one of the 25 study children had a score equal or below the lower quartile of age matched normal children.

The majority of children had not mastered the principles of multiplication/division (9/12 for the right group and 13/13 for the left group). Performance in both groups with respect to numbers of errors in complex addition and subtraction, errors in number facts, errors in number comprehension and production, attentional and dysphasic errors and total time of test was similar. However, the performance of the left group was worse than that of the right in 3 areas: mastery of addition/subtraction, visuo-spatial errors and number of errors in complex multiplication and division. The odds of the left group for
being classified as non-master of addition/subtraction was 19.8 times greater than the odds of the right group (p < .05); for having more visuo-spatial errors, the odds were 12.6 times greater for the left group than the right (p < .05). The left group also made more errors in complex multiplication and division (p < .05). The mean adjusted number of errors in multiplication for the left group was 9.2 (out of a possible 10 errors) and 7.0 for the right while for division it was 10.2 (out of a possible 11) for the left and 7.7 for the right (p < .05).

**DISCUSSION**

We studied the relationship between hemisphere dysfunction and the types and severity of arithmetic errors made by children with DD. Unlike Rourke (1989, 1993) or Hécaen et al. (1961), we were unable to identify patterns of arithmetic errors which were specific to right or left hemisphere dysfunction. However, children with left hemisphere dysfunction were the more severely impaired. They made more mistakes in complex multiplication and division and had a lesser degree of mastery of addition and subtraction. Their performance was inferior to that of children with right hemisphere dysfunction even in visuo-spatial tasks relating to arithmetic. In other domains of arithmetic functions, including those delineated in the cognitive model of arithmetic (McCloskey et al., 1985), i.e. number comprehension, number production and some aspects of calculation processing, no significant differences were identified between the 2 groups.

Rourke (1989, 1993), in his studies of children with dyscalculia, found that children with nonverbal learning disabilities (presumed right hemisphere dysfunction) made a large number and a wide range of error types, whereas children with associated reading disorders made mistakes either related to their disability in reading or inexperience with the subject material. Hécaen et al. (1961) correlated the neuropsychological deficit in adults with acquired dyscalculia to the type of arithmetic error. Those with visuo-spatial deficits from right hemisphere lesions had arithmetic errors due to inability to align numbers in space and carry out the other number manipulations contingent upon intact spatial representations. Patients with aphasic dyscalculia resulting from left hemisphere lesions misnamed numbers because of anomia and as result their calculations were wrong. Anarithmetia is the loss of mastery of the arithmetic operations, e.g. addition, multiplication, subtraction and division resulting from left hemisphere or diffuse bihemispheric lesions. The theoretical basis for this classification has been questioned by Grafman et al. (1982); in their study, patients with lesions in the posterior areas of the left hemisphere were most severely impaired and made more of all error types, including visuo-spatial related errors. This left hemisphere bias was also found to pertain to children and adolescents with acquired lateralized brain lesions: arithmetic deficits were more profound with left hemisphere lesions (Ashcraft et al., 1992). Studies on split brain patients indicate that the left hemisphere is superior to the right both in its ability to do calculations (Sperry et al., 1969) and to recognize digits (Teng and Sperry, 1973). Our results on children with DD are most compatible
with the observations of Grafman et al. (1982) and those in split-brain subjects. Hemispheric localization in children with unilateral lesions is still a controversial subject but the available evidence indicates that acquired dyscalculia in children can be a symptom with either left or right hemisphere lesions. In the study by Vargha-Khadem, O’Gorman and Watters (1988), arithmetic performance on the WISC subtest was not a discriminatory factor between left or right hemisphere lesioned children. On the other hand, Hécaen (1983), observed that dyscalculia was a major neuropsychological deficit only in children with left hemisphere lesions and Kiessling, Denckla and Carlton (1983) reported that arithmetic achievement is correlated with lack of right hemisphere impairment. Studies of developmental arithmetic disorders also suggest that both hemispheres have a significant role in the acquisition of arithmetic skills. Compromised functional integrity of either the right or left cerebral hemisphere has been documented in children with developmental dyscalculia (Rourke and Fisk, 1988). DD is a major criterion in the developmental right hemisphere syndrome (Weintraub and Mesulam, 1983) and other syndromes associated with visuo-spatial dysfunction, e.g. Turner’s syndrome (Money, 1973) and Fragile X (Kemper, Hagerman, Ahmad et al., 1986). The bilaterality of arithmetic function is also supported by the fact that there is no specific neuropsychological profile for children with poor school performance in arithmetic (Gordon, 1988). This contrasts with developmental dyslexia, for which a neuropsychological profile was found favoring visuo-spatial functions over verbo-sequential skills not only in the dyslexic child but also for other members of the family who are normal readers (Gordon, 1980).

In conclusion, our study demonstrates that in DD there is no specific pattern of arithmetic impairment which can be correlated with hemispheric dysfunction. We suggest that the acquisition of arithmetic skills is hierarchal in nature, dependent upon input from both hemispheres at different stages of learning. Therefore a developmental problem in either hemisphere will hamper the normal learning process. Although there seems to be more impact of left hemisphere dysfunction on acquisition of arithmetic skills, impairment of either hemisphere adversely affects the normal learning process of arithmetic.

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