Disabilities of Arithmetic and Mathematical Reasoning: Perspectives From Neurology and Neuropsychology

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Abstract

Current research on brain–behavior relationships in disabilities of arithmetic and mathematical reasoning is reviewed from both a neurological and a neuropsychological perspective. Although no entirely satisfactory statement of the relationship between arithmetic skills and brain functions has yet emerged, investigators in this area have provided evidence regarding the involvement of some brain systems in processes of calculation. Also, the developmental importance of right- versus left-hemisphere integrity for the mediation of arithmetic learning and performance has been suggested. We propose that an account of brain–behavior relationships in children intended to explain and predict developmental disabilities of arithmetic learning needs to address several important content and processing distinctions in order to (a) encompass empirically derived subtypes of children with learning disabilities who exhibit difficulties with arithmetic and (b) provide adequate direction for future subtyping and intervention research.

For many years, discussions of learning disabilities (LD) were mostly limited to unexpected developmental difficulties with functions such as reading and spelling. Although disorders of calculation have a fairly long history in the neurological literature, extending at least as far back as the early years of this century, work in this area was primarily concerned with acalculia as an acquired disorder resulting from brain damage incurred after a relatively normal course of early development. The study of dyscalculia as a developmental disorder, and more specifically as a subtype of learning disability, is of much more recent origin. Despite a massive literature on reading and other disabilities that appear to be linked very closely to disorders of language, there remains a relative lack of research concerning disabilities of arithmetic (Badian, 1983).

This state of affairs has resulted, in part, from the significance that arithmetic calculation had in early formulations of brain–behavior relationships. For example, many early neurological reports of patients with disordered calculation ability considered this symptom to be a manifestation of aphasia, and this perspective was eventually generalized to accounts of the relationship between developmental dyscalculia and dyslexia. From this perspective, arithmetic is a derivative skill having a basis in linguistic competencies, and the persistence of this assumption has undoubtedly hampered progress in the study of arithmetic disabilities. Moreover, social and cultural factors have influenced our evaluation of the relative importance of this topic. It has been suggested that having deficient arithmetic skills is generally considered to be more "socially acceptable" than having an impairment of reading, writing, or spelling (Cohn, 1968).

Several investigators have determined the prevalence of arithmetic disability to be at least 6% (e.g., Badian, 1983; Kosc, 1974). Kosc studied a large sample of Czechoslovakian children and found that 24 of 375 (6.4%) fifth graders were dyscalculic according to his definition. Badian reported incidence rates of poor achievement (a score at or below the 20th percentile on the Stanford Achievement Test) for a sample of 1,476 children in Grades 1 through 8, and concluded that 2.2% were low only in reading, 3.6% only in mathematics, and 2.7% in both reading and mathematics. The total number of students who demonstrated poor arithmetic ability with or without associated reading difficulty was 94 (6.4%), which is identical to the incidence rate reported by Kosc. It is clear that difficulties with arithmetic are by no means rare. Given the arithmetical demands of education, employment, and the many activities of daily living, current estimates of the prevalence of arithmetic disabilities should be taken as further evidence of the need for continued research in this area (Keller & Sutton, 1991).

In the present review, we examine the historical and conceptual roots of arithmetic disabilities as these have unfolded in the literature of neurology and neuropsychology. We attempt to outline what is known about the neurological substrates of calculation, with an eye toward relating this information to the neuropsychological correlates of disordered arithmetic learning ability. Acquired acalculia and developmental disabilities of arithmetic and mathematical reasoning each raise some interesting questions concerning lateralization and localization of function. Furthermore, disabilities of arithmetic learning have provided particularly good examples of how the identification of specific subtypes of LD has led to a richer understanding of the unique patterns of neuropsychological assets and deficits displayed by these children, as well as to developmental models of central processing deficiencies in children (Rourke, 1982, 1987, 1988, 1989; Rourke & Fisk, 1988).

The implications of these views for research and intervention with children with arithmetic disabilities flow from two premises. First, a distinction can be drawn between calculation as a discrete function and the more general context of arithmetic/mathematics learning and performance in which it occurs. Second, mathematical reasoning is but one dimension of the more general concept-formation and problem-solving skills necessary for successful learning, and a distinction can be drawn between the brain–behavior connections pertinent to successful acquisition of arithmetic skills and those on which well-learned performance depends.

Historical Overview

Acquired Acalculia and the Neurological Approach

Notions of the brain as the organ of thought and behavior received considerable prominence in the writings of Descartes (1596–1650), who "localized" the mind in the pineal gland. Interest in the relationship between the human brain and calculation ability can be traced back to the first attempts at localization of function, specifically to the phrenological theory of Franz Josef Gall (1758–1828) and Johann Casper Spurzheim (1776–1832; see Kolb & Whishaw, 1990; Levin, Goldstein, & Spiers, 1993). The resemblance of phrenological theory to modern theories of localization of function warrants the following discussion.

The anatomists Gall and Spurzheim believed that they could ascribe particular functions to different parts of the brain by examining the various bumps and depressions of the skull and correlating them with an individual's behavioral characteristics. A convexity was assumed to reflect a well-developed underlying cortical gyrus, responsible for a particularly well-developed behavioral function, and a depression indicated underdevelopment of that area and its functional correlate. Despite the fact that the outer surface of the skull does not mirror its inner surface, much less the surface of the brain, Gall and Spurzheim proceeded to "locate" a number of behaviors, including calculation. These investigators apparently found that the temporal area of the skull, just behind and above the eye, tended to show a protrusion in mathematicians and mathematical prodigies, leading them to conclude that the organ of calculation is located "in a convolution on the most lateral portion of the external, orbital surface of the anterior lobes" (cited in Levin et al., 1993).

Phrenology was quickly dismissed by the scientific community and was replaced by more sound methodologies including the experimental ablation techniques of Pierre Flourens (1794–1867) and the clinico-anatomical correlations of Paul Broca (1824–1880). Flourens's experiments with animals argued against localization of function but nevertheless set the stage for the rapid advances that would begin with the work of Broca in the 1860s. Broca demonstrated that damage to the third frontal convolution of the left hemisphere could abolish speech, and thus began the scientific study of localization of function in the human brain.

The neurological approach to brain–behavior relationships has traditionally been greatly concerned with issues of localization, drawing upon both idiographic and nomothetic observations in order to relate specific behavioral deficits to focal lesions of the central nervous system (CNS). Many early investigators relied heavily on individual case studies, partly because comparable subjects were few and far between and statistical knowledge was limited. The detailed examination of an individual case has remained a common and fruitful method for examining disorders of calculation, having certain advantages over a contrasting-groups approach. Of particular importance to the present context are the rich descriptions of the different types of arithmetic errors made by individuals whose disabilities might otherwise be lumped together under the general heading of acalculia. Error analysis of impaired arithmetic has resulted in more sophisticated classification systems, as well as in greater understanding of the component processes involved (Spiers, 1987).

Lewandowsky and Stadelmann (cited in Levin et al., 1993) were the first to publish a detailed case study that focused on an acquired disruption of calculation ability, distinct from aphasia and resulting from focal brain damage. Their patient had a right homonymous hemianopsia (no vision in the right half of the visual field) and difficulties with both written and mental calculation. The patient was described as often being unable to recognize arithmetic symbols, despite intact ability to follow the necessary computational procedures. Based on their observations of this patient, Lewandowsky and Stadelmann suggested that a specific type of alexia for numbers could result in a person being able to recognize individual digits while being unable to read several combined digits as a single number. Levin et al. suggested that this resulted from an inability to apply the rules of the propositional system. Believing their patient's difficulties to be based in visual factors, Lewandowsky and Stadelmann proposed the left occipital region as the "centre for arithmetic faculties." Their paper was historically significant in that it was the first to propose that disorders of calculation resulted from a focal lesion that was distinct from one producing aphasic symptoms. Furthermore, they described a specific type of alexia for numbers that they considered to be separate from alexia for letters or words (Levin et al., 1993).

The first statistical analysis of a large number of cases was reported by Henschen (cited in Levin et al., 1993), who was also the first to apply the label "Akalkulia" to disturbances of computational ability associated with brain damage. He suggested that the neural substrate for calculation was distinct from, but proximal to, that of language, with lesions of the left angular gyrus being implicated in nonaphasic patients exhibiting alexia and agraphia for numbers. Henschen analyzed 305 cases of calculation disturbance reported in the literature, in addition to 67 of his own patients, and determined the existence of a small subgroup of persons in whom brain damage had resulted primarily in a disturbance of calculation, with little or no aphasic symptoms. Similar results were obtained by others (e.g., Singer & Low, 1933), providing further evidence that the neural substrate of calculation ability was anatomically distinct from that of language, and that the deficits producing acalculia may occur independently of aphasia (Badian, 1983; Levin et al., 1993).

Henschen's observations were soon followed by the work of Berger (1926), who proposed the distinction between primary and secondary acalculia. According to Berger, primary acalculia refers to a specific disruption of calculation ability and cannot be attributed to more generalized difficulties in prerequisite abilities, such as short-term memory or sustained attention. Secondary acalculia, on the other hand, refers to a symptom resulting from either a specific primary deficit (e.g., aphasia) or a more pervasive disruption of brain function. Generalized brain dysfunction may disrupt calculation performance via impairment of any number of prerequisite skills and abilities, including language, memory, attention, and cognition (Levin et al., 1993). According to Berger, primary acalculia is attributable to posterior left-hemisphere lesions not necessarily invading the angular gyrus, whereas secondary acalculia results from diverse focal lesions, or generalized damage (Benton, 1987).

In a seminal work on the classification of acalculias, Hécaen, Angelergues, and Houillier (1961) performed a detailed error analysis and proposed a tripartite organization based on the presumed neuropsychological mechanisms underlying each type. The work of Hécaen et al. exemplifies the modern neurological approach, in which calculation is analyzed into its component processes, specific types of acalculia are derived from the nature of the errors that are characteristic of such patients, and an attempt is made to systematically relate those different types of acalculia to particular cortical regions. The classification of acalculia into three types, presented below, continues to have a strong influence on the study of disorders of arithmetic, and many investigators still employ this scheme with very little modification:

Type 1. *Acalculia resulting from alexia and agraphia for numbers, in which the patient is unable to read or write the numbers required for successful calculation.* Although this form of acalculia has been referred to as *aphasic acalculia* (Benson & Weir, 1972), it is not limited to aphasic patients. This form of disrupted calculation may occur independent of an inability to read or write linguistic material and has been correlated mainly with posterior left (and sometimes bilateral) cerebral lesions (Hécaen, 1962).

Type 2. *Acalculia of the spatial type* is associated with impaired spatial organization of numbers, such as misalignment of digits in columns, inversions (6 for 9), reversals (12 for 21), visual neglect, and difficulties maintaining the decimal place. This type of acalculia is believed to be produced by posterior right-hemisphere damage or dysfunction. Hécaen et al. (1961) found this type of acalculia to be 12 times more frequent in right- versus left-hemisphere lesions.

Type 3. *Anarithmetria* refers to a disruption of calculation per se. This would be considered a primary acalculia within the Berger (1926) dichotomy; it refers to an inability to carry out arithmetic procedures despite intact visual–spatial skills and the capacity to read and write numbers. As with acalculia secondary to alexia and agraphia for numbers, anarithmetria was found to be predominantly associated with posterior left or bilateral lesions. However, approximately 20% of these patients had right-hemisphere lesions, a finding that emphasizes the difficulty of attempting strict localization of calculation ability without regard to the presenting phenotype.

The research of Hécaen and his colleagues has been of considerable heuristic value in the study of brain–behavior relationships in calculation. Their classification system and clinicopathological correlations led to many testable propositions that have been the basis of numerous detailed studies of the relationship between acalculia and other neurological and neuropsychological impairments (e.g., Dahmen, Hartje, Büssing, & Sturm, 1982; Grafman, Passafiume, Faglioni, & Boller, 1982). Furthermore, many of the basic concepts contained in the works of Henschen, Berger, and Hécaen have proved to be essential ingredients in the identification and classification of developmental disorders of calculation. For example, these authors pointed out that disordered arithmetic is not a univocal phenomenon but, rather, can result from the disruption of quite different underlying mechanisms.

The various sources of disordered arithmetic performance may involve calculation per se, one or more of its component processes, a prerequisite skill, or even a generalized impairment of which disordered calculation is merely a secondary symptom. All of these ideas have extended to the study of arithmetic LD, whether as part of a conceptual framework guiding the interpretation of empirical data or as premises in arguments from analogy. The latter point has particular import for the study of arithmetic and related LD, because much of the theorizing in this area has relied heavily on inferences made from studies of adults (Semrud-Clikeman & Hynd, 1990). Only rather recently has a substantial body of child/developmental data and data on model-building with respect to arithmetic LD begun to emerge (e.g., DeLuca, Rourke, & Del Dotto, 1991; Rourke, 1982, 1987, 1988, 1989; Rourke & Fisk, 1988; Share, Moffitt, & Silva, 1988; White, Moffitt, & Silva, 1992).

Gerstmann Syndrome

Josef Gerstmann published a series of articles from 1924 to 1930 that described a constellation of four behavioral deficits that were reported to appear together as a syndrome. These deficits include the following: bilateral finger agnosia (inability to identify one's fingers by touch alone), right–left confusion, dysgraphia (disrupted ability to write), and dyscalculia. There does not appear to be any specific type of calculation disturbance that is characteristic of the Gerstmann syndrome (Hartje, 1987). Developmental Gerstmann syndrome (DGS) has also been proposed, and a fifth symptom, constructional dyspraxia, is often included in this classification (Kinsbourne, 1968; Kinsbourne & Warrington, 1963). According to Gerstmann (1940), the aggregate appearance of these deficits was related to focal damage or disease in the territory of the angular gyrus of the dominant (usually left) hemisphere.

Subsequent investigations, however, revealed that these deficits do not necessarily always appear together. Rather, each of them may appear in isolation, or they may appear as partial groupings in which only two or three are present in a particular individual (Heimburger, DeMyer, & Reitan, 1964). Furthermore, it was found that patients with all four Gerstmann symptoms invariably had large lesions involving the superior temporal and supramarginal gyri as well as the angular gyrus. Heimburger et al. found no case of full Gerstmann syndrome in which damage was limited to the angular gyrus, and in 3 of 23 such patients the angular gyrus was not involved at all. In addition, some patients with left angular gyrus lesions showed no Gerstmann symptoms. These clinico-anatomical comparisons are consistent with statistical analyses revealing that these deficits are no more strongly correlated with each other than they are with such deficits as poor visual memory, dyslexia, or constructional dyspraxia (Benton, 1961).

Consequently, it has been suggested that the Gerstmann syndrome is an artifact of biased observation and should not be considered a true clinical syndrome. However, damage or dysfunction in the parietal–occipital region of the language-dominant hemisphere does seem to be associated with the behavioral deficits described by Gerstmann, and the utility of the label persists despite its questionable status as a distinct diagnostic entity (Gaddes, 1985). More recent reports have presented cases that fit the syndrome and its proposed anatomical basis quite well. Although the syndrome remains largely an enigma, it appears to have some heuristic value and may, in fact, be a more common manifestation of developmental disabilities than was previously thought to be the case (Benton, 1992; Grigsby, Kemper, & Hagerman, 1987; PeBenito, Fisch, & Fisch, 1988; Spellacy & Peter, 1978). For example, Grigsby et al. reported on a group of children with Fragile X syndrome who exhibited three or more Gerstmann symptoms without any evidence of aphasia, as well as one boy with Fragile X who exhibited all five DGS symptoms. They concluded that DGS is in fact a clinical entity, and that a variety of partial symptom groupings from this syndrome are relatively common in children with Fragile X syndrome. It should also be noted that these symptoms form part of the syndrome of nonverbal learning disabilities (NLD; Rourke, 1989), the neuropsychological assets and deficits of which have been shown to characterize many forms of pediatric neurological disease, disorder, and dysfunction (Rourke, 1995).

Gerstmann syndrome is included in the present discussion not only because dyscalculia is one of its defining features, but also because it represents one of the first examples of a neuropsychological description of arithmetic LD. In fact, children with developmental Gerstmann's syndrome bear more than a passing resemblance to a subtype of children with arithemetic disabilities identified by Rourke and his colleagues (Rourke & Finlayson, 1978; Rourke & Strang, 1978; Strang & Rourke, 1983) using a developmental neuropsychological approach. As we will see, this approach raises some interesting questions regarding the differential specialization of the cerebral hemispheres in general, as well as the neuropsychological bases of arithmetic and mathematical reasoning in particular. In addition to providing a developmental model of central processing deficiencies in children, these studies have demonstrated that deficient performance in arithmetic can result from vastly different patterns of neuropsychological assets and deficits (Rourke, 1993).

Relevance of Adult Studies

There is, of course, some question as to whether knowledge obtained from the study of adults generalizes well to brain–behavior relationships in children. There is little doubt that analogies drawn between childhood and adult syndromes are conceptually useful and may provide a first step in the development of clinical classifications (Denckla, 1973). However, in many respects, the behavioral manifestations of brain damage in adults differ quite dramatically from those seen in children. This is a consequence of a number of interacting factors, including the nature of the damage, its location within the CNS, and the premorbid skills of the individual. For example, the type of damage most typically seen in adults differs from that seen in children. Focal intracerebral lesions resulting from cerebral vascular accident, tumor, or penetrating head injury are more common in adults, whereas more generalized impairments arising from perinatal trauma, anoxia, inborn errors of metabolism, or closed-head injury are typical of children. In short, brain disorders of childhood have been far less likely to be subject to strict anatomic delimitation, neuroimaging, neurosurgical intervention, or pathological inspection (Boll & Barth, 1981). However, this state of affairs is beginning to change dramatically for many brain diseases of childhood, including hydrocephalus (Fletcher, Brookshire, Bohan, Brandt, & Davidson, 1995) and traumatic brain injury (Ewing-Cobbs, Fletcher, & Levin, 1995).

Adults also bring a history of established function, learned skills, and accomplishment to the clinical or research situation. This history of premorbid development can result in a very different picture of brain–behavior relationships in adults than in children, who differ not only in terms of their skills and consequent strategies, but also in terms of the amount of change in these that is to be expected over time. Whereas adults exhibit relatively static brain–behavior connections, such relationships in children are of a much more dynamic nature. In children, the relevant issue is not only the loss or disrupted acquisition of specific skills, but also the impact that various neurodevelopmental impairments have on the order, rate, and level of future development and learning capacity. The effect that CNS damage or dysfunction will have on a child's arithmetic performance is very much a function of the child's current and future developmental demands as well as the neuropathological characteristics of the damage (Rourke, Bakker, Fisk, & Strang, 1983).

Consequently, consideration of the impact that various types of brain impairment may have on the developmental course of events may be more informative vis-à-vis brain–behavior relationships in arithmetic disabilities than via simply attempting to relate particular abilities to specific brain systems or regions. This is not to say that the lessons learned from a neurological approach to acalculia do not have relevance for the study of children with different subtypes of arithmetic LD: It is apparent that children so classified come by their difficulties with arithmetic for distinctly different reasons, and the relevance of different approaches to such disabilities depends on the specific nature of the subtype of arithmetic disability in question. It is clear that the conceptualization of some subtypes of arithmetic learning disability is greatly enhanced via comparison of those subtypes to documented cases of brain damage in both adults and children. However, it is also the case that some children exhibit a subtype of arithmetic LD that is better conceptualized in neurodevelopmental terms that bear little or no resemblance to neurological models of acalculia. It is precisely these distinctions that need to be addressed before detailed subtyping of arithmetic LD can proceed.

Developmental Dyscalculia

Developmental dyscalculia has been relatively neglected compared to acalculia in adults or dyslexia in children. This is apparent in the absence of widely accepted criteria for its definition in research or its diagnosis in clinical settings. Kosc (1974) presented one of the most thorough discussions of this problem, with an emphasis on hereditary or congenital factors that may compromise the integrity of neural substrates of calculation ability. Based on evidence from a number of neurological, neuropsychological, and genetic studies, Kosc argued that developmental dyscalculia is properly considered to be a reflection of brain dysfunction, and defined it as follows:

> Developmental dyscalculia is a structural disorder of mathematical abilities which has its origin in a genetic or congenital disorder of those parts of the brain that are the direct anatomico-physiological substrate of the maturation of the mathematical abilities adequate to age, without a simultaneous disorder of general mental functions. (Kosc, 1974, p. 47)

This definition makes three essential points. First, developmental dyscalculia involves a specific impairment of mathematical abilities, within the context of normal general mental abilities. This is essentially the same point that is made by authors attempting to define the term *learning disability*, distinct from definitions of mental retardation or other general intellectual impairment. Second, developmental dyscalculia is defined and identified according to the relationship that exists between the child's current mathematical abilities and those that can be considered normal for his or her age. Only through a careful age-appropriate analysis of the child's assets and deficits can a significant and "pathological" impairment be discerned. Third, dyscalculia is a developmental affliction distinguished from acquired forms of acalculia occurring in adulthood. Thus, the term *developmental dyscalculia* is reserved for those disorders that have their origins in "hereditary or congenital impairment of the growth dynamics of the brain centers, which are the organic substrate of mathematical abilities" (Kosc, 1974, p. 48). This formulation suggests that the crucial impairment depends more on the developmental sequence of the acquisition and refinement of progressively more complex neurocognitive systems than on calculation per se. This notion stands in marked contrast to the notion of developmental dyscalculia as a static impairment of calculation centers in the brain.

In addition to identifying essential defining features, Kosc (1974) classified six subtypes of developmental dyscalculia. Four of these subtypes can be seen to bear a resemblance to the adult forms of acalculia described above; others appear to reflect uniquely developmental dimensions of the disorder. For example, Kosc described "verbal dyscalculia," in which there is a disruption of the ability to name mathematical terms and relations. These children have difficulty naming amounts and numbers of objects, operational symbols, and even digits and numerals. He also described a "lexical dyscalculia" (with impairment of the ability to read mathematical symbols, including digits, numbers, and operational signs) as well as "graphical dyscalculia" (in which the disability is manifested as a difficulty with writing numbers and operational symbols).

These patterns of impairment are similar to those reported by Hécaen et al. (1961) for adults with alexia and agraphia for numbers, in whom the functional integrity of the perisylvian regions, especially of the left hemisphere, is implicated. Kosc (1974) also described "operational dyscalculia," which is a direct impairment of the ability to carry out arithmetic operations per se. This form of developmental dyscalculia appears to be roughly equivalent to Hécaen's anarithmetria (Hécaen, 1962; Hécaen et al., 1961). However, it is unlikely that anatomical inferences from adult cases of anarithmetria are directly applicable to operational dyscalculia in children.

Kosc (1974) also proposed "practognostic" and "ideognostic" dyscalculias. Practognostic dyscalculia refers to a disturbance of the ability to manipulate real or pictured objects for mathematical purposes. This includes problems with enumerating a group of objects and estimating and comparing quantities. These children are unable to set out objects in order according to magnitude, show which of two items is bigger or smaller, or correctly indicate when two objects are the same size. Ideognostical dyscalculia is an impairment of the ability to understand mathematical ideas and relations required for mental calculation. Such persons may be able to read and write numbers but cannot understand what they have written. For example, the child might read the digit "9" but be unable to understand relations such as that 9 is half of 18, or is 1 less than 10, or is equivalent to 3×3 (Kosc, 1974).

It is interesting to note that the difficulties referred to as "practognostic" bear a striking resemblance to Piagetian tasks. A more recent study demonstrated that two 9-year-old boys who were unable to acquire elementary numerical skills and who exhibited deficits associated with Gerstmann syndrome had not progressed to the concrete operational stage of cognitive development (Saxe & Shaheen, 1981). Both children believed that changing the visual–spatial configuration of either a continuous or a discontinuous quantity actually changed its amount.

It would seem likely that practognostic and ideognostic forms of dyscalculia reflect fundamental impairments in, or failure to develop significant dimensions of, more basic concept-formation and nonverbal reasoning abilities. Neuropsychological studies of children with arithmetic LD, discussed below, have provided clues to a possible source of such atypical cognitive development.

Cerebral Asymmetry and Disabilities in Arithmetic

Understanding brain–behavior relationships in children who exhibit disabilities of arithmetic and mathematical reasoning requires at least a general familiarity with some issues surrounding cerebral asymmetry. It has been known for some time that the left and right cerebral hemispheres are not precise mirror images of each other; this applies to both their structure and their function. Each hemisphere has its own particular penchants, with some relatively straightforward lateralization of function being empirically demonstrable. The most well-known difference between the cerebral hemispheres is that the left hemisphere is usually dominant for language functions, whereas systems within the right hemisphere usually predominate in the processing of nonverbal stimuli. Such differences have been demonstrated in intact subjects using methods such as dichotic listening (Kimura, 1963), tachistoscopic stimulus presentations (Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990), task-related EEG asymmetries (Doyle, Ornstein, & Galin, 1974; Earle, 1985; Rebert, Wexler, & Sproul, 1978), and average evoked potentials (Davis & Wada, 1977; Galin & Ellis, 1975; Licht, Bakker, Kok, & Bouma, 1992). Furthermore, these interhemispheric differences in function appear to have an anatomical basis. It has been reported that the left hemisphere tends to be slightly heavier and larger in most right-handed persons, with the largest differences being found in areas that mediate language functions (e.g., the planum temporale; Galaburda, LeMay, Kemper, & Geschwind, 1978; Geschwind & Levitsky, 1968).

Analyses of neuropsychological deficits arising from right- versus left-hemisphere lesions led some early investigators to speculate that the cellular organization of the left hemisphere is more close-knit and integrated than that of the right hemisphere (Hécaen & Angelergues, 1963). For example, visual–spatial deficits often result from lesions occurring over a broad range of areas within the right hemisphere, whereas deficits arising from left-hemisphere damage tend to be associated with more specific lesion sites (De Renzi, 1978; De Renzi & Faglioni, 1967). Furthermore, there is evidence to suggest that the overall functioning of the right hemisphere is more easily disrupted, even by relatively small lesions (Kertesz & Dobrowolski, 1981). Further support for this position comes from observations that tactile discrimination is more often disrupted bilaterally by right-hemisphere lesions than is the case with left-sided lesions, which tend to produce only contralateral tactile deficits (Semmes, 1968). As will be discussed later, this latter finding has some import for the neuropsychological profile analysis of one subtype of children with arithmetic LD.

More comprehensive theoretical accounts of these and other observations have been formulated by Goldberg and Costa (1981) and Rourke (1982). Goldberg and Costa incorporated anatomical and behavioral evidence into their theory of cerebral asymmetry, which holds that the left hemisphere is specialized for the processing of unimodal stimuli and routinized behavioral acts, whereas the right hemisphere is specialized for intermodal integration, processing of novel stimuli, and dealing with informational complexity. In particular, they pointed out that the structure of the left hemisphere is marked by the presence of three prominent opercula (clumps of gray matter) in the temporal, parietal, and posterior frontal regions, each of which appears to mediate relatively discrete and routinized functions (such as those involved in linguistic processes). Focal damage to one of these opercula tends to produce rather specific deficits, with other areas of the left hemisphere continuing to function in a surprisingly independent fashion. This arrangement can be contrasted with that of the right hemisphere, in which the prominent organizational feature is a higher ratio of white matter relative to gray matter, which appears ideally suited to the integration of complex information arriving through a number of sensory modalities. According to Goldberg and Costa, this results in an advantage; and a propensity for the processing of novel and/or complex stimuli, and this general organizational principle renders the right hemisphere more susceptible to generalized dysfunction arising from virtually any form of significant insult to its overall integrity.

Any attempt to relate arithmetic and mathematical ability to cerebral asymmetry must necessarily take into account the specific nature of the skill or ability under investigation. Phrenological notions of a single process or set of processes mediated by a calculation center in the brain have long since been abandoned and have yielded to more sophisticated accounts of how the brain might mediate these behaviors and abilities. Although the left hemisphere is generally believed to mediate the numerical symbol system, retrieval of number facts from semantic memory, and simple linear equations with an $a + b = c$ form (Geary, 1993; Lezak, 1983; Spiers, 1987), the right hemisphere undoubtedly plays an important role in mathematical performance that requires adaptive reasoning and/or visual–spatial organization of the elements of the problem (Rourke, 1993). Examples of the former would include the use of multiplication table values and story problems such as those found in the Arithmetic subtest of the Wechsler Adult Intelligence Scale–Revised (Wechsler, 1981). Examples of the latter type of task would depend partly on the strategy employed by the individual, but it is probably safe to assume that most persons draw on visual–spatial abilities during the procedures required for long division and multiplication.

In adults, mathematical performance appears to be mediated largely by the posterior association cortex, with left-sided lesions resulting in loss or disruption of basic arithmetic operations and number facts, including the concept of number itself. Right-sided lesions produce deficits in dealing with the visual–spatial–organizational dimensions of calculation and mathematical reasoning, such as using decimal places and "carrying" and "borrowing" (Grewel, 1952). However, this situation is greatly complicated by developmental dimensions and interactions. Superimposed on this already complex picture of brain–behavior connections for arithmetic performance is the added dimension of a developmental sequence of events that may become disrupted at a number of different points or stages. In turn, points in the developmental sequence of events probably differ in terms of the nature and location of CNS damage or dysfunction that will most negatively affect subsequent developmental events.

A Neurodevelopmental Approach to Arithmetic Disabilities

In a series of studies conducted from the 1970s to the present, Rourke and colleagues have described two subtypes of children with LD who exhibit equally impaired levels of arithmetic achievement but have vastly different profiles of neuropsychological assets and deficits (Rourke, 1993). Those studies were undertaken to determine the neuropsychological significance of different patterns of academic achievement. Previous studies examining Verbal IQ–Performance IQ discrepancies in children (Rourke, Dietrich, & Young, 1973; Rourke & Telegdy, 1971; Rourke, Young, & Flewelling, 1971) revealed predictable patterns of performance on Wide Range Achievement Test (WRAT; Jastak & Jastak, 1965) Reading, Spelling, and Arithmetic subtests. The subsequent studies were conducted to determine if children with specific subtypes of LD, identified by their patterns of performance on the WRAT, would also demonstrate predictable patterns of neuropsychological assets and deficits (Rourke, 1993).

The first study in that series examined three groups of children with LD between the ages of 9 and 14 years who were equated for age and Wechsler Intelligence Scale for Children (WISC) Full Scale IQ (Rourke & Finlayson, 1978). Group 1 children were uniformly deficient in reading, spelling, and arithmetic; Group 2 participants performed significantly better (although still below age expectation) in arithmetic than in reading and spelling; and Group 3 children had markedly impaired arithmetic performance within a context of normal reading and spelling ability. All three groups exhibited impaired arithmetic performance, but only Groups 2 and 3 were equivalent, performing significantly better than Group 1 on the WRAT Arithmetic subtest. It is important to note that Groups 2 and 3 exhibited equally impaired levels of arithmetic performance, despite having very different overall profiles of achievement.

The results of the Rourke and Finlayson (1978) study indicated that Groups 1 and 2 performed significantly better than Group 3 on neuropsychological measures of visual–perceptual and visual–spatial abilities, whereas Group 3 performed significantly better on verbal and auditory–perceptual measures. Furthermore, children from Groups 1 and 2 exhibited a pattern of Verbal IQ < Performance IQ, whereas Group 3 children exhibited the opposite pattern, having lower Performance than Verbal IQs. These findings were interpreted as reflecting differential hemispheric impairment between the groups. That is, the findings were consistent with the hypothesis that children in Groups 1 and 2 had some impairment (i.e., relatively deficient functional integrity) of left-hemisphere systems, whereas Group 3 children exhibited the effects of compromised right-hemisphere functioning.

These inferences were based on the fact that subjects in Group 3 did particularly poorly only on those tasks thought to be subserved primarily by systems within the right cerebral hemisphere, whereas subjects in Groups 1 and 2 were deficient only on those tasks thought to be subserved primarily by systems within the left cerebral hemisphere. From this it was inferred that Groups 2 and 3, despite demonstrating equally impaired levels of arithmetic, differed in terms of the neuropsychological bases of those deficits. Group 2 children were apparently experiencing difficulties with arithmetic due to verbal deficiencies, whereas Group 3 children appeared to be encountering greater difficulty with the visual–spatial and nonverbal reasoning dimensions of arithmetic performance.

To explore the possibility that these groups were exhibiting differential impairment of right- versus left-hemisphere systems, Rourke and Strang (1978) examined the performances of these same three groups on measures of motor, psychomotor, and tactile–perceptual skills. The results indicated that Group 3 children were deficient, relative to both age norms and the performance of Groups 1 and 2, on complex psychomotor and tactile–perceptual skills, especially when using the left hand. This provided further evidence in support of the hypothesis that Group 3 children were experiencing their difficulties in arithmetic as a result of relatively deficient right-hemisphere systems, as opposed to Group 2 children, whose difficulties were apparently arising from compromised systems within the left hemisphere. Consistent with the present emphasis on arithmetic learning disabilities, the remainder of this review will focus on the performances of Groups 2 and 3 only. As previously mentioned, these two groups exhibited equally impaired levels of arithmetic achievement, apparently for very different reasons. The situation with respect to Group 1 is far more complex because it is probably the case that it is made up of a number of different LD subtypes (Fisk & Rourke, 1979).

A third investigation in the series (Strang & Rourke, 1983) compared the performances of children in Groups 2 and 3 on the Halstead Category Test (Reitan & Davison, 1974), a complex measure of nonverbal concept formation involving abstract reasoning, hypothesis testing, and the ability to benefit from positive and negative informational feedback. These adaptive dimensions of behavior, in addition to visual–spatial difficulties, were hypothesized to be instrumental in the arithmetic difficulties exhibited by Group 3 children. The two previous studies had demonstrated that Group 3 children exhibited a configuration of neuropsychological deficiencies that would have implications for their cognitive development in terms of Piagetian theory (Piaget, 1954). That is, these children's tactile–perceptual, psychomotor, and visual–perceptual–organizational deficiencies were seen as serious liabilities in terms of their being able to benefit from the early sensorimotor experiences that Piaget described as underlying the transition to later stages of cognitive development and acquisition of higher order cognitive skills. It is noteworthy that the participants in Saxe and Shaheen's (1981) study, who had not progressed to Piaget's concrete operational stage of cognitive development, exhibited neuropsychological profiles that were strikingly similar to those of Group 3 children.

As expected, Group 3 children made significantly more errors on the Category Test than did Group 2 children. Although the Halstead Category Test should not be considered a direct measure of right-hemisphere integrity, the development of higher order cognitive skills required for success on this measure is thought to be dependent on very basic developmental skills and abilities that appear to rely heavily on right-hemisphere systems for their successful elaboration (Rourke, 1989). That is, deficient performance on the Category Test was interpreted as reflecting a disordered pattern of development, and although this pattern was attributed to early neuropsychological deficits that appear to reflect relative dysfunction of systems within the right cerebral hemisphere, this does not imply that performance on the Category Test is lateralized to the right.

TABLE 1
Neuropsychological Assets and Deficits of Group R-S and Group A

Group	Assets	Deficits
R-S	Tactile perception	Auditory perception
	Visual perception	
	Psychomotor skills	
	Attraction to novelty	
	Tactile attention	Auditory attention
	Visual attention	Verbal attention
	Exploratory behavior	
	Tactile memory	Auditory memory
	Visual memory	Verbal memory
	Concept formation	
	Problem solving	
	Mathematical reasoning	
	Scientific reasoning	
	Linguistic prosody	Linguistic phonology
	Linguistic semantics	Verbal reception and repetition
	Linguistic content	Verbal storage
	Linguistic pragmatics	Verbal associations
	Linguistic function	Verbal output (volume)
A	Auditory perception	Tactile perception
	Simple motor skills	Visual perception
	Absorbing rote material	Psychomotor skills
		Aversion to novelty
	Auditory attention	Tactile attention
	Verbal attention	Visual attention
		Exploratory behavior
	Auditory memory	Tactile memory
	Verbal memory	Visual memory
		Concept formation
		Problem solving
		Mathematical reasoning
		Scientific reasoning
	Linguistic phonology	Linguistic prosody
	Verbal reception and repetition	Linguistic semantics
	Verbal storage	Linguistic content
	Verbal associations	Linguistic pragmatics
	Verbal output (volume)	Linguistic function
		Verbatim memory

Note. For a full explanation of these neuropsychological profiles, see Rourke (1989, 1995).

Based on the results of these three studies (see Table 1 for a summary), the following conclusions can be drawn regarding the neuropsychological significance of the two subtypes of children who exhibit arithmetic disabilities. First, at least two distinctly different patterns of neuropsychological assets and deficits can eventuate in arithmetic LD. Whereas Group 2 (now referred to as Group R-S) children exhibit normal levels of performance on visual–spatial–organizational, psychomotor, and tactile–perceptual tasks, Group 3 (now referred to as Group A, or the Nonverbal Learning Disabilities [NLD] subtype) children perform at impaired levels on these measures. Furthermore, children with NLD tend to encounter increasing levels of difficulty as the task demands become more novel and complex. In contrast, these children exhibit well-developed auditory–perceptual skills, especially for material that is amenable to rote verbal learning. Children of the R-S subtype have outstanding difficulties in these areas, especially with the complex semantic–acoustic aspects of the linguistic domain. It appears that Group R-S children encounter their difficulties with arithmetic as a result of verbal deficits that reflect relative impairment of left-hemisphere systems, whereas Group A (NLD) children are limited by nonverbal deficits that implicate relatively dysfunctional right-hemisphere systems.

Second, Group R-S children perform well on measures of nonverbal problem solving and concept formation. They exhibit intact capacities to benefit from nonverbal informational feedback, as well as from past experience with such tasks. This stands in marked contrast to the performance of NLD children, who exhibit outstanding deficits in these areas. This raises the question of whether NLD children are experiencing the cumulative effects of a disrupted sequence of developmental events. Their pattern of neuropsychological deficits may have affected early sensorimotor experiences, which in turn served to skew the normal course of cognitive development. The interested reader may wish to consult Rourke (1989, 1995) and Rourke and Fuerst (1995) for elaborations of the developmental dynamics of NLD children.

It is apparent that there is a need for further subtyping studies of arithmetic LD. As the above series of studies clearly demonstrates, a univocal conceptualization of arithmetic disabilities is simply not adequate to the task of understanding the unique assets and deficits of these children, or of developing adequate programs of intervention. Arithmetic LD can result from at least two very broad classes of neuropsychological impairment, one based on verbal deficiencies (probably reflecting relatively dysfunctional left-hemisphere systems) and one based on nonverbal deficiencies (which appear to reflect the phenotypical out-come of early impairment of, or lack of access to, systems within the right hemisphere). Evidence from studies of evoked potentials in children who exhibit these subtypes of LD strongly suggests that the conclusions with respect to relative hemispheric integrity are well founded. (For a review of those studies, see Dool, Stelmack, & Rourke, 1993.)

In view of the considerations alluded to above, each of these two subtypes of arithmetic LD may be divisible into more fine-grained subtypes. For example, in reference to the work of Hécaen et al. (1961) and Kosc (1974), it may be the case that children whose difficulties with arithmetic are attributable to verbal factors can be divided into two or more subtypes. That is, some of these children may have a variant of alexia and agraphia for numbers, whereas others may encounter difficulties with arithmetic secondary to more general linguistic deficiencies, difficulties retrieving number facts from semantic memory, or even discrete impairment of calculation per se. On the other hand, children whose difficulties with arithmetic are attributable to primarily nonverbal deficits may represent both a visual–spatial subtype and a nonverbal concept formation/adaptive reasoning subtype. However, in view of considerations regarding the marked tendency for right-hemispheral systems to be disrupted by significant impairment of virtually any locus, the latter would seem much more complicated than the formulations proposed by Hécaen and by Kosc. Other considerations with respect to a more fine-grained analysis of children whose disabilities in learning appear to be rooted in linguistic deficiencies are dealt with in Rourke (1989, Chapter 8). The important points to emphasize at this juncture are that advances in the characterization of brain–behavior relationships in children with arithmetic LD are dependent on a more precise specification of the subtype of disordered arithmetic in question, and that this awaits further investigative effort.

Summary and Conclusions

As we have seen, the neurological approach to acalculia is, for the most part, concerned with localizing the particular component processes of arithmetic by correlating focal brain lesions with particular numerical deficits or types of errors. Mathematical performance is analyzed into its components, specific types of acalculia are derived, and an attempt is made to determine if these vary systematically with disease or dysfunction of particular cortical regions (Benton, 1987). The neurological approach has yielded a number of important inferences regarding the cerebral organization of mathematical abilities and, by analogy, these have informed efforts to elucidate relevant brain–behavior connections in children. It would appear that the component processes of arithmetic performance can be effectively dissociated (Geary, 1993; Spiers, 1987), and it is clear that clinico-anatomical correlations have provided compelling evidence for the differential involvement of particular cortical regions in these component processes (Hartje, 1987; Hécaen, 1962; Hécaen et al., 1961; Keller & Sutfon, 1991).

This neurological approach has considerable conceptual utility for the examination of developmental disorders. The neuropsychological study of LD, however, is concerned more with phenotypic levels (i.e., manifest patterns of academic performance) and the relationships of these to more basic neuropsychological assets and deficits. A neuropsychological approach to LD is oriented toward the full range of brain–behavior relationships that may interact with or affect the arithmetic learning situation. In this approach, a systematic attempt is made to relate brain systems to the different ways in which arithmetic learning may be impeded. This can involve something as specific as retrieval of number facts from semantic memory, or as general as concept formation, nonverbal reasoning, and adaptive problem solving. Developmental neuropsychological deficits may involve calculation per se, difficulties with the visual–spatial demands of arithmetic performance, or a developmental lag or disruption that alters the child's normal course through the Piagetian stages of cognitive development.

The neurological approach to acalculia has yielded inferences that may seem somewhat contradictory to the findings from neuropsychological studies of children. The most prominent of these is that studies of adults implicate mainly the left cerebral hemisphere as being more important for calculation ability, whereas studies of children indicate that the right- and left-hemispheral systems are crucial to the development and elaboration of skills and abilities relating to the learning of arithmetic and mathematics. There are two broad reasons why findings from the study of acalculia in adults differ from many of the inferences drawn from neuropsychological studies of children.

First, a distinction can be drawn between a discrete impairment of the cortical "function" of calculation, or even one or more of its component processes, and the more general context of arithmetic learning and performance. Undoubtedly, the cognitive and neuropsychological demands of executing learned calculation skills differ considerably from those of initial arithmetic learning and performance in children. Whereas the former would rely heavily on previous rote learning and the retrieval of number facts from semantic memory, the latter seems much more dependent on the early maturation of concept formation and adaptive reasoning skills. Thus, a distinction can be made between the brain–behavior relationships that are relevant to the execution of learned calculation skills and the brain–behavior relationships that are relevant to the initial appreciation of prerequisite concepts and problem-solving skills required for successful arithmetic learning.

Second, according to the models proposed by Goldberg and Costa

(1981) and Rourke (1982, 1989), the integrative, complex, and novel dimensions of early mathematical learning and concept formation would be expected to draw heavily upon the resources of right-hemispheral systems. Only after successful initial learning would number facts and basic arithmetic procedures become sufficiently routinized to be executed primarily by left-hemispheral systems. Thus, elements of arithmetic that were once very novel, conceptual, and even visual–spatial in nature for the child become automatic in the adult, even to the degree that many so-called calculations are merely specific instances of fact retrieval from semantic memory. The prediction regarding brain–behavior relationships that emerges from this view is that early damage or dysfunction in either hemisphere will disrupt arithmetic learning in the child, with very profound effects to be expected from early right-hemisphere insults, whereas left-hemisphere lesions will predominate in the clinicopathological analysis of acalculia in adults. Our review of the literature suggests that this is the case.

Finally, issues of prediction and intervention are of paramount importance in any examination of children with LD. In the past, early identification of children at risk for disabilities in arithmetic was markedly neglected. It is now clear that neuropsychological assessment can reveal patterns of assets and deficits in children that are predictive of later academic performance, including arithmetic. More specific predictions of the types of difficulties likely to be encountered by these children will inform efforts to develop adequate programs of intervention (Rourke & Tsatsanis, 1965).

Although a detailed discussion of intervention in disabilities of arithmetic is beyond the scope of this article, it is clear that the views expressed herein have practical implications for the management of these children. The efficacy of an intervention program cannot be adequately assessed if the children in such a program have differing needs resulting from vastly different neuropsychological assets and deficits. Intervention programs tailored to the specific needs of arithmetic disability subtypes (e.g., Rourke, 1989, 1995; Rourke & Tsatsanis, 1995) are amenable to empirical investigation of their effectiveness, thus allowing for the modification and continued development of such efforts. In terms of overall progress in the field of learning disabilities, it is this heuristic dimension that represents the unique value of the study of brain–behavior relationships in children, including those with problems in arithmetic calculation.

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