Pediatric Neurology 61 (2016) 11–20

Contents lists available at ScienceDirect

Pediatric Neurology

journal homepage: www.elsevier.com/locate/pnu

Topical Review

Dyscalculia and the Calculating Brain

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ABSTRACT

Dyscalculia, like dyslexia, affects some 5% of school-age children but has received much less investigative attention. In two thirds of affected children, dyscalculia is associated with another developmental disorder like dyslexia, attention-deficit disorder, anxiety disorder, visual and spatial disorder, or cultural deprivation. Infants, primates, some birds, and other animals are born with the innate ability, called subitizing, to tell at a glance whether small sets of scattered dots or other items differ by one or more item. This nonverbal approximate number system extends mostly to single digit sets as visual discrimination drops logarithmically to “many” with increasing numerosity (size effect) and crowding (distance effect). Preschoolers need several years and specific teaching to learn verbal names and visual symbols for numbers and school agers to understand their cardinality and ordinality and the invariance of their sequence (arithmetic number line) that enables calculation. This arithmetic linear line differs drastically from the nonlinear approximate number system mental number line that parallels the individual number-tuned neurons in the intraparietal sulcus in monkeys and overlying scalp distribution of discrete functional magnetic resonance imaging activations by number tasks in man. Calculation is a complex skill that activates both visual and spatial and visual and verbal networks. It is less strongly left lateralized than language, with approximate number system activation somewhat more right sided and exact number and arithmetic activation more left sided. Maturation and increasing number skill decrease associated widespread non-numerical brain activations that persist in some individuals with dyscalculia, which has no single, universal neurological cause or underlying mechanism in all affected individuals.

Keywords: dyscalculia, learning disability, intraparietal sulcus, subitizing, numerosity, number line, functional magnetic brain imaging, remediation

Pediatr Neurol 2016; 61: 11-20

Introduction

The goal of this review is to update child neurologists and other professionals concerned with developmental disorders about the brain basis of much neglected calculation and dyscalculia. Parents of children with isolated academic problems without physical abnormality, epilepsy, overt language or cognitive deficiency, or unacceptable behaviors are likely to have heard or read of spectacular advances in genetics and neuroscience. They may consult child neurologists or other physicians seeking an up-to-date explanation for their child’s unexpected developmental problem, asking whether there is a test or medication that might help. Most physicians see few school-age children with “pure” dyscalculia because it is considered the responsibility of educators and school psychologists. Neurologists need to be able to convey to parents the important biologic implications of advances in neuroscience research, stressing that they are not clinical diagnostic tools or likely to help in the management of the individual child with dyscalculia or other pure developmental disorders. Although neurologists will likely be asked about genetic contributions to dyscalculia,[1-4] up-to-date knowledge of the genetics of brain development exceeds the competence of most practitioners and the scope of this review.

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0887-8994/$ – see front matter © 2016 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.pediatrneurol.2016.02.007

Definition and prevalence

Dyscalculia applies to any otherwise competent child who fails to learn at the expected age that number names refer, one-to-one, exclusively and sequentially, to each item in any set of objects, including their own ten fingers, and, later, to Arabic symbols, and to estimates of the approximate number (numerosity) of items in the set (approximate number sense—ANS). Failure to grasp the abstract concept of number (cardinality), let alone the place principle (ordinality), means calculation eludes such children. Calculation, like reading, is a culturally derived, specifically taught, slowly learned skill. It calls for the ongoing interaction of environmental experiences with multigenetically influenced development of visual, spatial, and language proficiency, working and long-term memory, focused attention, motivation, and other intellectual and executive competences. Dysfunction of any one or more of these abilities can contribute to difficulty or failure to acquire an understanding of numbers. This means that dyscalculia, like dyslexia, is not a single disorder attributable to a single gene abnormality, unique cognitive deficiency, or maldevelopment or damage affecting one specific brain locus or pathway.[5-7] For instance, among 378 eight-year-old German-speaking children with a performance intelligence quotient greater than 85, von Aster and Shalev[8] reported a 6% prevalence of dyscalculia, but only 1.8% (a third of those affected) with pure dyscalculia, compared with 4.2% in whom dyscalculia was associated with another prevalent developmental disorder like dyslexia, attention-deficit disorder,[9] or anxiety.[10] Similarly, among 50 11- to 13-year-old Swedish children with developmental dyscalculia, 16 (32%) were considered to have a specific deficit accessing number concepts and the 34 others (68%) more general problems with calculation.[6]

There are some standardized tests of various calculation skills, but none that is universally accepted; therefore prevalence estimates rest on school reports. The prevalence of dyscalculia approximates that of dyslexia, some 5% to 6% of elementary school children.[11-13] Yet an October 24, 2015, PubMed search (by S.R. Snodgrass) retrieved 615 papers on epidemiology of dyslexia and 15 (2.4%) on dyscalculia; there were 96 on brain networks in dyslexia and 15 on networks in dyscalculia. This disparity shows how much less research attention dyscalculia has attracted despite comparable prevalences[8] and even though measurement and calculation ability is becoming ever more critical in our technologically driven society.[13]

Children's acquisition of number skills

von Aster and Shalev[8] describe four stages in children's acquisition of number competence: (1) In neonates, toddlers, and persistently throughout life, subitizing (from *subito*, quick, sudden) is the innate nonverbal ability to detect at a glance a difference in number of items between two small arrays of up to four or so randomly placed items.[14] Humans share this ability with monkeys and also with some birds and even invertebrates like bees.[15,16] (2) Preschoolers learn by rote the verbal labels for counting, usually at first as an undifferentiated sequence of single digit names without referents. Only by age three to four years does the average preschooler acquire gradually, one-by-one, the name of the numeral that applies specifically to one object, then to two, then three, then four, and so on, progressively developing a more abstract sense of exact number and learning that each name symbolizes a specific number, irrespective of the size or appearance of its referent.[17] The child needs time to understand the uniqueness (cardinality) of each number, that they occur always in the same counting order (ordinality), and, eventually, that the last digit name provides the exact total number of items in any serially counted set. By kindergarten most children will count reliably five to ten randomly spaced objects without repetition or skipping, indexing their gradual grasp of both cardinality and ordinality of numbers. (3) By first grade they will have learned to link number names to the visually coded Arabic digit symbols and to understand that adding one or subtracting one from a set yields the next bigger or smaller number of items in the set. They become progressively able to give fast memorized verbal answers to single-digit addition and subtraction of numbers up to five, and will have discovered the utility of their fingers for calculation.[18,19] (4) Only at this stage will many elementary school children find out that you can count items serially across several sets to yield the total of their union.

Children will typically require two or three more years to memorize rote answers to addition and subtraction of larger single digits and to visualize the spatial representation of consecutively larger numbers on the linear number line as scaffold for ordinality and mastery of the decimal system. Mental arithmetic with small numbers is subject to much practice in the first grades of school, although probably somewhat less today thanks to ubiquitous cell phones and other calculators. Automatic answers to overlearned single digit calculations and, after several years, to multiplication tables up to five, by tens and, mostly less securely, to the six to nine times tables, generally become coded verbally for long-term storage, thus bypassing the need for repeated mental computation.[20,21] In contrast to single-digit addition and multiplication, the reverse operations, subtraction and division, are less likely to be automatized and continue to call for more cognitive resources and more widespread brain circuitry[22,23] (Fig 1).

Cognitive and cellular basis of number skills in man and monkey

Together, subitizing and the ANS are the representatives of the cardinality and ordinality of numbers in the brain.[25] In contrast to fast and accurate innate subitizing, perhaps with limited capacity,[26] ANS accuracy and response speed decrease rapidly as number increases (magnitude effect),[14] with a precipitous drop for crowded uncountable numbers, i.e., "many." High-strength functional magnetic resonance imaging (fMRI) in normal adults shows the clearest topographic number tuning in the right posterior superior parietal lobe, with small numbers of dots (one to seven) in displays more narrowly tuned and allocated more cortical space than larger ones whose tunings are progressively broader and overlapping.[27] Thus cortical representation of the nonverbal visual ANS is analogous to that of other sensory estimates like sound pitch, weight, temperature, and