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The Cognitive Origins of Mathematics Learning Disability: A Review

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Mathematics learning disability, or dyscalculia, is a specific learning disability that affects an individual's ability to learn about and process numerical or mathematical information. Although estimates vary, it is thought to affect between 5 and 8 percent of the population. The purpose of this article is to provide a brief review of the history of mathematics learning disability as well as to present some competing hypotheses regarding the cognitive nature of mathematics learning disability. Finally, we provide some recommendations for further reading.

Keywords: mathematics learning disability, dyscalculia, magnitude, working memory

Mathematics learning disability (also known as developmental dyscalculia) is a specific learning disability that is characterized by an impaired ability to learn about and process numerical and mathematical information that is not attributed to general intellectual disabilities (American Psychiatric Association, 2013). Although estimates vary widely, it is currently thought that mathematics learning disability occurs in approximately 5 and 8 percent of the population (Butterworth, 2005; Shalev, 2007; Shalev, Manor, & Gross-Tsur, 2005).

Whereas much research has been conducted on the nature of mathematics learning disability, several issues remain unclear. First, not much is known about how mathematics learning disability develops (Geary & Hoard, 2005). Furthermore, there are conflicting hypotheses on what exactly goes wrong (cognitively and neurologically speaking) when someone develops mathematics learning disability (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013). Finally, while there are ample studies on mathematics learning disability in children, relatively few studies approach the issue in the context of adulthood.

The purpose of this review is twofold. First, we wish to provide the reader with a brief, (but by no means comprehensive) history of mathematics learning disability from a diagnosis standpoint. In addition, we talk at length about some competing hypotheses regarding the exact cognitive deficits that may underlie mathematics learning disability. As such, we will also discuss the nature of numerical and mathematical cognition in general, particularly from the standpoint of mental representations of number. Finally, we will provide the reader with a short list of readings that we consider fundamental in gaining a profound understanding of this important topic.

A Brief History

Historically, the concept of mathematics learning disability has been synonymous with the term dyscalculia. Although dyscalculia applies broadly to individuals with deficits in numerical representation and processing, *acalculia* was the prevalent term in early literature. Henschen (1925) used the term acalculia to refer to an *acquired* weakness in computation that directly resulted from brain injury; the term dyscalculia was reserved for weaknesses that resulted from genetic or congenital defects. Calculation disturbances were described in earlier literature, but most often as a consequence of aphasia. In the 1920s, Josef Gerstmann described a syndrome referring to a cluster of deficits, including finger agnosia, right-left disorientation, dysgraphia, and dyscalculia (Bakwin & Bakwin, 1966). Hence, even though mathematics disabilities were identified, they were often viewed as occurring together with, or as a function of, other neurological impairments.

Later studies generally went against this trend. Lewandowsky and Stadelmann (as cited in Boller & Grafman, 1983), separated acalculia from language deficits in a 1908 report describing a shipping clerk who lost his ability to calculate after the removal of hematoma from the left occipital lobe. Based upon their study of 50 patients with brain lesions, Poeck and Orgass (1966) argued that the disturbances in Gerstmann's syndrome were independent from other neurological disorders. Similarly, subsequent researchers continued to establish that the mathematical deficits evident in patients with brain injuries could exist independently, without deficits in other domains. Going further, Berger (as cited in Ardila & Rosseli, 2002) even distinguished between primary and secondary acalculia, attributing the deficits in primary acalculia to a "pure" loss of mathematical ability and those in secondary acalculia to other cognitive factors.

Much of this research in this period was focused on the question of identifying the nature of dyscalculia from a neurological standpoint. It was not until 1962 that dyscalculia entered the realm of education. At this time, as the education of atypical learners was moving to the sociopolitical forefront, Samuel Kirk introduced *learning disability* into the lexicon of special educators. From the standpoint of the special education community, the primary interest in dyscalculia was in its identification and remediation, not in understanding its cause. It is at this point that one begins to see dyscalculia labeled as *mathematics learning disability*.

As an early definition, the notion of learning disabilities encompassed the deficits of children who were delayed in specific domains without the presence of mental retardation (Kirk & Bateman, 1962). In 1969, the term *specific learning disability* became a federally designated special education category through the Specific Learning Disabilities Act (PL 91-230). This was followed closely by the Education for All Handicapped Children's Act (PL 94-142). Since the inception of these acts, the federal definition of a specific learning disability has included the requirement of a *discrepancy* between ability and achievement. This stipulation was consistent with the research at that time (see Rutter & Yule, 1975), thus bringing into practice the use of intelligence (IQ) and achievement tests for identification of learning disabilities, including mathematics learning disability.

Until the recent past, the discrepancy method has remained the gold standard for diagnosis of mathematics learning disability. In order to meet diagnostic criteria using this method, an individual's mathematical performance as measured by an achievement test (e.g., the *Woodcock Johnson*) must be lower than expected based upon aptitude (e.g., as measured by a Weschler intelligence scale). According to Sternberg and Grigorenko (2002), there are numerous reasons to abandon the discrepancy model, including the obvious issues arising from the movement towards a more multifaceted theory of intelligence (see Gardner, 1983).

As a result of the President's Commission on Excellence in Special Education, the most recent version (2004) of the Individuals with Disabilities Act (IDEA) requires the development of alternatives to the discrepancy model in identifying children with learning disabilities. *Response to intervention* (RTI) approaches call for the use of evidence-based interventions for struggling students, with those not responding to interventions being moved along a three-tiered process towards diagnosis. Early indications are that RTI is improving services to children, although there are issues with validity and reliability in diagnosis (Sullivan & Castro-Villarreal, 2013).

In keeping with public policy and trends in education, the American Psychiatric Association removed the discrepancy requirement for diagnosis of a specific learning disorder in the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5). What remains, however, is the continued requirement for deficit in at last one academic skill area. Scanlon (2013) criticizes the definition, arguing that there is little guidance for diagnosing learning disorders outside of a school setting. This is particularly problematic for adults, for whom the impact of deficits in math at home and work could be critical. Unfortunately, there seems to be little agreement on what exactly constitutes a diagnosis for mathematics learning disability, especially for adults. This is most certainly an area for further research.

The Cognitive Factors Behind Mathematics Learning Disability

Even though mathematics learning disability has been subject to a rich history of inquiry over the last century, its development and exact nature remain a puzzle. However, most research indicates that the source seems to stem from cognitive deficits in the systems that are crucial to processing numbers (Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007). These core systems include domain-specific abilities, such as the ability to form and manipulate mental representations of quantity (Mazzocco, Feigenson, & Helberda, 2011) and magnitude (Mussolin, Mejias, & Noël, 2010) and to automatically convert between symbols and numerical magnitudes (Rubinsten & Henik, 2005; Rouselle & Noël, 2007). Other core systems that may be implicated in mathematics learning disability involve domain-general abilities, in particular deficits in working memory and executive functioning (Toll, Van der Ven, Kroesbergen, & Van Luit, 2011) and attentional capacity (Ashkenazi & Henik, 2010, 2012).

The purpose of the following section is to review these different perspectives on the source of mathematics learning disability. Particular attention will be paid to the empirical methods used across these studies, as they represent a standard battery of cognitive tests that are often used in studies on numerical cognition.

Deficits in the Processing of Quantity

One widely accepted view of how people mentally represent numbers fractionates our abilities into two different systems. One system is a precise, symbolic number system that supports calculation and higher mathematics (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999), and the other is an approximate, nonsymbolic system that is used both in nonsymbolic tasks (e.g., deciding which array of items is more numerous) as well as in symbolic tasks that involve Arabic numerals (Feigenson, Dehaene, & Spelke, 2004).

Each system is reflected by a unique psychophysical effect that occurs in experimental settings. For example, when people are asked to judge which of two numbers presented on a computer screen is larger (a symbolic task), people tend to make the judgment more quickly when the numbers are farther apart (e.g., 7 is larger than 1) than when the numbers are closer together (e.g., 7 is larger than 6). This *numerical distance effect* (Moyer & Landauer, 1967) is widely found across a large array of cognitive arithmetic tasks. Its presence is typically taken as a marker for processing of numerical magnitude. One hypothesis is that since mental representations of numbers have some inherent variability, numbers that are close together in magnitude will have a degree of *representational overlap*, and the overlap results in a slower decision regarding which one is the larger number (Dehaene, 1992).

To put it more concretely, consider Figure 1. In this figure, the bell-shaped curve centered over each number represents a mental representation of that number; that is, the amount of activation that each number of the number line receives when a person thinks about a specific number, say 5. According to the figure, 5 receives the greatest activation, but so do the numbers 4 and 6, albeit to a lesser extent. That is, our mental representation of the number 5 is a bit "fuzzy". When comparing numbers that are close together (e.g., 8 and 9), their curves have a large amount of overlap. Hence, it takes more time to resolve which one is larger, compared to the situation when numbers are farther apart (e.g., 4 and 9) and have less overlap.

In terms of individual differences, the size of the numerical distance effect (as indexed by the correlation between distance and reaction time) is thought to reflect the nature of an individual's tendency to have less precise representations of numerical magnitude (Holloway & Ansari, 2009). For example, an individual with a larger numerical distance effect would essentially have more overlap between their mental representations of number, and hence, less precise representations. This notion has proved to be valid on a number of levels, particularly in the sense that individuals with larger numerical distance effects tend to exhibit lower performance on simple arithmetic tasks (Holloway & Ansari, 2009).

The functioning of the approximate number system (ANS) is assessed in a fundamentally different way. Being a nonsymbolic system, the ANS is typically as-

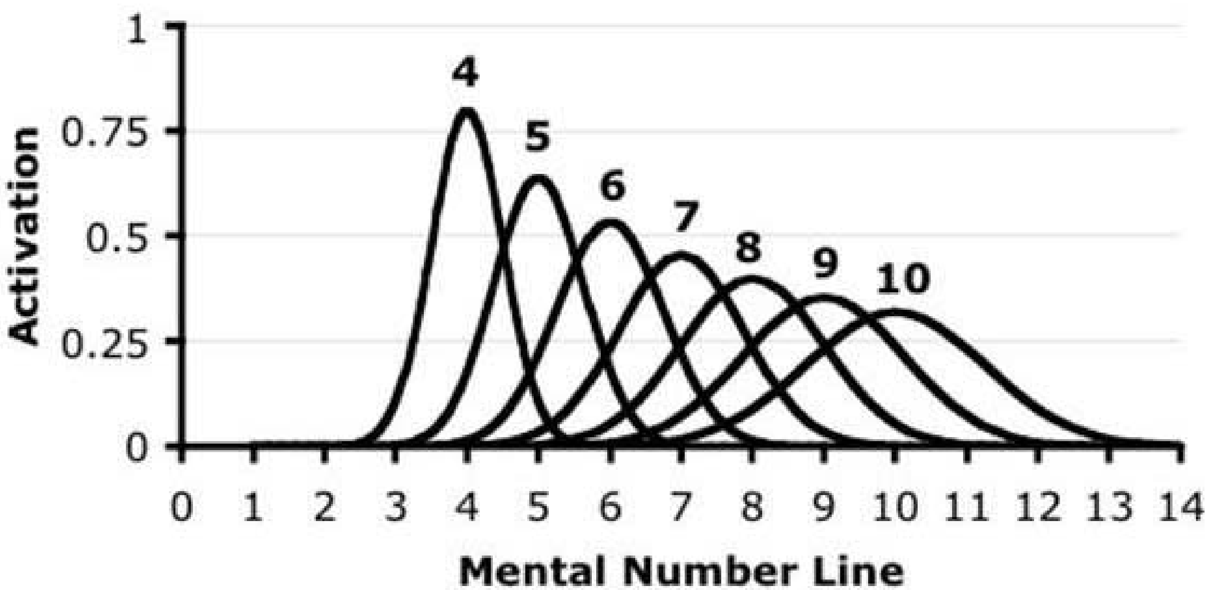

Figure 1. Mental representations of number depicted as activation curves centered on each number with increasing standard deviations. Adapted from www.panamath.org

sessed through a quantity comparison task in which participants discriminate the relative numerosity of two arrays of objects. In one variety of this task (the *Panamath* task; www.panamath.org), an array of dots in two different colors is presented on a computer screen for a very short amount of time, and the participant is asked to judge which color represents the more numerous (see Figure 2). Since the presentation time is too short to allow counting, this task is thought to rely on our approximate representation of number. As a quantitative index of individual performance on this task, a number called the Weber fraction w is computed. While a detailed account of the Weber fraction is beyond the scope of this review, it is enough to understand that w simply indexes an individual's approximate number representation. More detailed, one should note that as the ratio between two arrays approaches 1 (where the numerosities would be equal), individuals tend to make more errors in their numerosity judgements. The Weber fraction w is related to the rate of increase in these errors. Individuals with larger Weber fractions have "noisier" approximate representations of number, and this has been shown to be related to mathematics achievement (Halberda, Mazzocco, & Feigenson, 2008). Particularly, individuals with larger Weber fractions tend to do worse in an array of mathematical tasks than those individuals with smaller Weber fractions.

Two recent studies have lent considerable evidence to the claim that mathematics learning disability results from a core deficit in the ability to represent numerical magnitudes. Mussolin, Mejias, and Noël (2010) ask 10- and 11-year old children to compare numbers presented in a variety of formats (both symbolic and nonsymbolic) to the reference quantity 5. Fifteen children were diagnosed with a mathematics learning disability if they scored normal with respect to verbal and spatial IQ measures, but performed below the 15^{th} percentile on a multiplication fluency test (as compared to a normative sample of elementary school children in the region of the study). These fifteen children were age-matched with 15 children who served as active controls. Mussolin et al. found that across all tasks, the children with mathematics learning disability showed no difference in performance (indexed by reaction time and error rates) compared to the control group. However, they did exhibit a larger numerical distance effect than did the children in the control group. That is, when plotting reaction time as a function of the distance between numbers to be compared, the children with mathematics learning disability exhibited a steeper negative slope. Using the interpretation of Holloway and Ansari (2009), this steeper slope implies that these children have a less developed sense of numerical magnitude than the children in the control group.

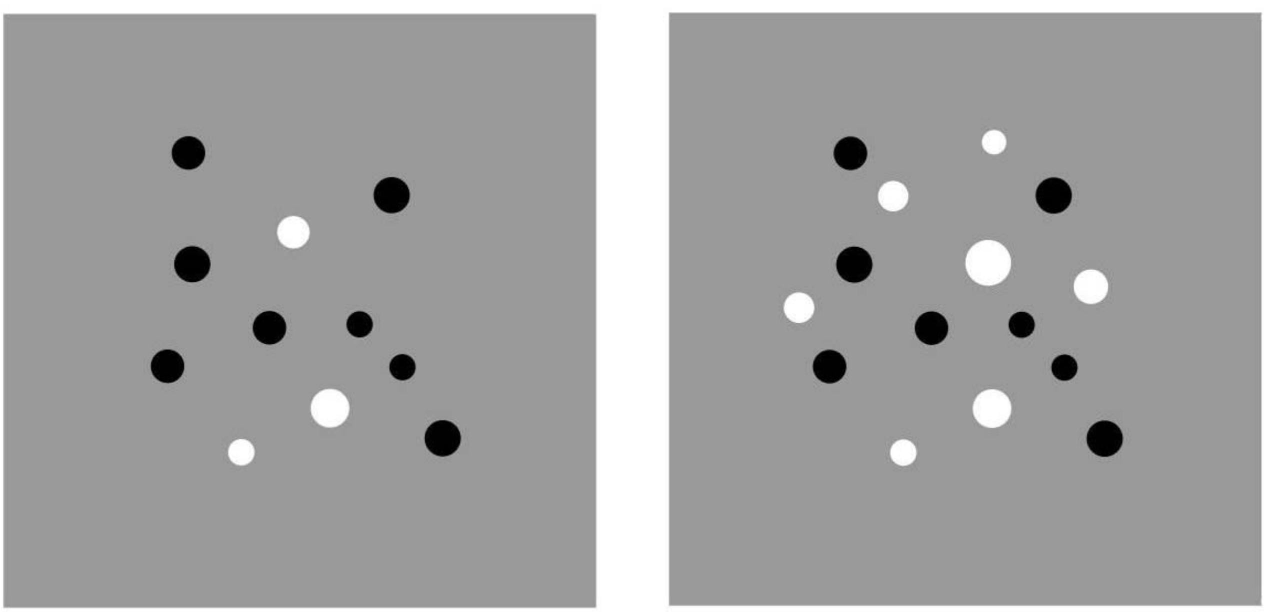

Figure 2. The Panamath numerical discrimination task. As the numbers of dots get closer, the task becomes more difficult. The Weber fraction w is related to an individual's pattern of errors as numerosities become more equal.

Whereas Mussolin et al. (2010) found that mathematics learning disability may stem from an underdeveloped sense of exact small number representation, Mazzocco, Feigenson, and Halberda (2011) found evidence that the impairment may lie in the *approximate* number system. Mazzocco et al. had 71 ninth-graders complete a nonsymbolic numerical discrimination task, the nature of which is identical to the Panamath task described above. That is, participants were asked to discriminate within a display of yellow and blue dots which color was more numerous. Since the presentation was very brief (200 ms), counting was ruled out as a strategy to complete the task. Thus, all judgements required an approximate sense of number rather than an exact, symbolic sense of number. From these numerosity judgements, a Weber fraction w was computed for each participant. Mazzocco et al. (2011) found that compared to students of varying achievement levels in mathematics (low achieving, typical achieving, and high achieving), the children with mathematics learning disability had a significantly larger Weber fraction w. That is, these children possessed a much less acute notion of approximate numerosity, lending evidence to the notion that mathematics learning disability stems from a deficiency in the approximate number system.

Deficits in Ability to Automatically Transform Symbols to Magnitudes

When people are asked to complete a numerical task, most children as well as adults process the magnitude of the underlying numbers automatically (Girelli, Lucangeli, & Butterworth, 2000). Particularly striking is the notion of *autonomous* automatic activation of number magnitudes (Tzelgov, Yehene, Kotler, & Alon, 2000), in which the automatic activations that occur are not part of the original task requirements. A classic example of this type of automatic processing is the Stroop effect (Stroop, 1935; MacLeod, 1991), whereby a person is slower to report the color of a word that itself is a color word. This slowdown in response time is indicative of people's tendency to automatically read a presented word, even though actually reading the word is not part of the task requirement. The interference between the task requirement (saying the color) and the automatically processed information (the word itself) requires extra processing time to resolve, and hence, the observable measure of increased reaction time.

In the domain of numerical cognition, a similar automatic processing effect occurs. In one common task, participants are asked to compare the physical sizes of two digits having different physical sizes (e.g., 2 and 9) and pick the digit that is presented in the larger size. Particularly, participants are told to ignore the numerical size of the digits (magnitude) and pay attention *only* to the physical size. In general, people tend to respond faster when the physically larger digit is also the numerically larger digit (congruent trials, e.g., 2 and 9) than they do when the physically *smaller* digit is the numerically larger digit (incongruent trials, e.g., 2 and 9). This Stroop-like effect, known as the *size congruity effect*, indicates that the numerical magnitudes associated with the Arabic symbols in the task are automatically activated even though they are actually irrelevant to the task. Furthermore, this effect doesn't appear in children until somewhere between first grade (Rubinsten, Henik, Berger, & Shahar-Shalev, 2002) and third grade (Girelli et al., 2000), suggesting that the ability to automatically convert symbols to mental representations of magnitude doesn't develop until the early school years.

Several recent studies have yielded evidence that people with mathematics learning disability may be lacking in their ability to perform this automatic symbols-to-magnitude conversion. Rubinsten and Henik (2005) compared the size congruity effect between a group of 19 college-aged adults with mathematics learning disability and a group of 19 age- and gender-matched control group of college-aged adults without mathematics learning disability. The control group exhibited the typical size congruity effect: they were approximately 125 ms faster to judge the physical size of two digits when the size and numerical magnitudes were congruent (e.g., 2 vs 8) compared to the incongruent condition (e.g., 2 vs 8). However, the mathematics learning disability group exhibited a smaller size congruity effect (approximately 75 ms) than did the control group. This difference led Rubinsten and Henik (2005) to conclude that adults with mathematics learning disability are not as apt to automatically convert between symbols and magnitude. Similar results with children were found by Rousselle and Noël (2007): children with mathematics learning disability exhibited a smaller size congruity effect than did a control group. Taken together, these results indicate that the source of mathematics learning disability may not be a defect in the ability to represent number magnitudes *per se*, but rather a defect in the conversion process between symbols and numerical magnitudes.

Deficits in Executive Functioning

While much research indicates that there may be number-specific impairments in people with mathematics learning disability, there is a large body of research concerning the role of domain-general cognitive resources such as working memory and executive functions. Recall that working memory is the cognitive system responsible for storing and manipulating information in the short term. As such, it is typically thought to comprise three independent components: the *central executive*, responsible for attentional control and resource planning; the *phonological loop*, responsible for maintenance and rehearsal of sound-based information; and the *visuo-spatial sketchpad,* responsible for maintenance and rehearsal of visual and spatial information (Baddeley, 1986).

Further work specified the structure of the central executive as consisting of three *executive functions:* shifting, inhibition, and updating (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Shifting refers to the ability to switch back and forth between multiple tasks and is often referred to as *task switching*. Shifting may be particularly useful in mathematical thought by helping people switch between alternate strategies and/or steps in a multi-step solution process (Bull, Espy, & Wiebe, 2008). Inhibition refers to one's ability to deliberately suppress automatic responses when necessary, such as the name of the color word in the Stroop task. Although lack of inhibition has been found in children with lower mathematical ability (Bull, Johnston, & Roy, 1999), other studies have indicated that this relationship may be spurious (Van der Sluis, De Jong, & Van der Leij, 2004). Finally, updating refers to monitoring and coding incoming information and appropriately revising outdated information with new, more relevant information. For example, when solving multistep arithmetic problems, one needs to be able to mentally coordinate information from long term memory (basic arithmetic facts, solution strategies) and update the answer to the problem as each step commences. Generally, updating is thought to be of critical importance to mathematical ability (see Raghubar, Barnes, and Hecht, 2010, for a review).

Several recent studies have questioned whether executive function impairment may be responsible for mathematics learning disabilities. In a two-year longitudinal study, Toll et al. (2011) administered measures of mathematical ability and of the three aforementioned executive functions to children in first- and second-grade. On the basis of performance on the mathematical tasks throughout the two years, the children were split into a typical achieving group and a low achieving group. Toll et al. (2011) found no differences between groups on measures of shifting and inhibition (see also Censabella and Noël, 2008), but they did find a significant group difference in measures of updating. Specifically, children who were low-achieving scored lower on updating measures than did typical-achieving children. Furthermore, these updating measures were better at predicting mathematics learning disabilities than were mathematical abilities alone. In general, it seems that of the three executive functions previously described, updating may be the only function implicated in the development of mathematics learning disability.

Recently, Ashkenazi, and Henik (2010) addressed the role of executive functions in mathematics learning disability from the perspective of *attentional networks*. Whereas classical definitions of attention define it as a unitary cognitive process akin to short-term memory, more recent research has viewed attention as comprising three separate networks (Posner & Peterson, 1990): the *alerting* network, which activates and preserves attention; the *orienting* network, which shifts attention to specific points in space; and *executive control*, which is responsible for monitoring and resolving conflict between task requirements. Ashkenazi and Henik (2010) found that college students with mathematics learning disability were deficient with respect to the alerting network and executive control. In an interesting followup, Ashkenazi and Henik (2012) had participants with mathematics learning disability complete a video-game training task in hopes of boosting these attentional network capabilities. They found that the training did improve the attentional deficits of those with mathematics learning disability, but no improvement was noted in basic numerical processing. This led Ashkenazi and Henik (2012) to conclude that mathematics learning disability results from domain-specific numerical deficits and not domain-general disabilities.

Summary and Further Reading

In general, there are three main hypotheses about the cognitive origins of mathematics learning disability. One view holds that mathematics learning disability stems from a core deficit in number sense, particularly the ability to represent and process both exact and approximate numerical magnitudes. In this view, both symbolic and nonsymbolic processing is affected. Another view holds that mathematics learning disability is the result of a defective ability to automatically transform symbols into their appropriate magnitude representations. Here, symbolic processing is affect whereas nonsymbolic processes are unaffected. Finally, the third view posits that mathematics learning disability stems from a domain-general deficit in working memory and attention rather than from math-specific deficits. There is ample evidence for each view, and the field is not yet to a point where enough is known to be able to separate these hypotheses from each other. This is still a very active field of research that will continue to flourish in the near future.

For the reader who wishes to learn more about mathematics learning disabilities or mathematical cognition in general, we recommend an article and two general-audience books below:

- Butterworth, B. (1999). *What counts: How every brain is hardwired for math.* New York, NY: The Free Press.
- Dehaene, S. (2011). *The number sense* (2nd ed.). New York, NY: Oxford University Press.

- Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37,* 4–15. doi: 10.1177/00222194040370010201

In conclusion, mathematics learning disability is an impaired ability to learn and do mathematics that affects a small, but significant portion of the population. Even though it has been studied for the better part of a century, its diagnosis is vague at best and its origins are not well understood. It is, however, an important area of study, and it likely will be for many years to come.

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