# What is developmental dyscalculia and what does it look like in the brain?

*Numbers pervade every aspect of our daily lives. Even without being professional mathematicians, we deal with numbers on a regular basis: when we compare prices at the supermarket, when we have to tell time, remember PIN codes, or even when we have to take the right bus-number.*

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## Executive summary

- *Developmental dyscalculia* (DD) refers to a specific learning disability which manifests in difficulties in acquiring adequate numerical and mathematical skills in the context of otherwise normal intelligence and appropriate education.
- DD develops during childhood and, without the appropriate intervention, often persists into adulthood with negative consequences for educational and professional outcomes.
- Recent evidence suggests that DD is characterized by alterations of multiple brain systems that are known to be critical for successfully solving numerical problems.
- The notion that DD is a deficit at the brain level, together with rapid advancements in neuroscience-based techniques, can help identify and develop more quantifiable ways to diagnose this condition, with important implications for its prevention and remediation.
- This work is in its infancy and needs to be accompanied by rigorous neuroscience studies that systematically assess how the brain typically develops to support the successful acquisition of math knowledge.
- By refining our understanding of how the brain successfully acquires math skills, we can start developing quantifiable indices to help characterize how, and at which level, the brains of children (and adults) with DD go "off course."

## Introduction

Numbers pervade every aspect of our daily lives. Even without being professional mathematicians, we deal with numbers on a regular basis: when we compare prices at the supermarket, when we have to tell time, remember PIN codes, or even when we have to take the right bus-number.

Developmental dyscalculia (DD) impedes these most basic numerical skills.

DD is defined as a specific developmental learning disability that manifests in difficulties in acquiring adequate numerical and mathematical skills in the context of otherwise normal intelligence and educational opportunities[1]. Individuals with DD struggle with the most basic arithmetical facts (e.g., *3+4 =7*) and, in some cases, even in telling which one is larger between *3* and *4*. DD develops during childhood and, without the appropriate intervention, it often persists into adulthood with negative consequences for employability, wages, and socioeconomic, physical, and psychological well-being.[2] Specifically, weak mathematical skills have been associated with: (1) inappropriate use of health resources (e.g., managing drug prescriptions), (2) poorer health outcomes (e.g., depression), (3) lower educational and professional opportunities, and (4) higher levels of criminality.[2] In its most severe form, DD affects 3 to 9% of the population.[3] Yet, up to 20% of individuals struggle to adequately acquire proficient arithmetic skills[4]. Such broad incidence-range suggests that DD can vary from individual to individual, mostly due to the fact that math knowledge is hierarchical in nature: the next ability to be learnt usually builds upon the previous one. Moreover, each set of abilities necessary to solve even the most basic arithmetic problems is supported by different regions of the brain and their interactions. Let us see how.

### Multiple brain regions are responsible for adequate numerical and mathematical development

As educated adults without DD, when we see an arithmetical operation such as "3+4 = …", immediately our brain goes "7." Since we find it so simple, we often forget (or we probably have never realized) how hard it is—for our brain—to initially learn how to solve such a simple arithmetic problem. First, our brain needs to have a "sense for quantity" (also called the *number sense*)[5,6]. That is, our brain needs to be able to "grasp" that *three items* is less than *four items*. Importantly, this is true regardless of item-type and item-size. In other words, a set of *three apples* and a set of *three hats* have the same *threeness*, and they are both less than a set of *four apples* and a set of *four hats*, no matter their size. The concept of quantity is therefore abstract—it could be applied to different items, with different properties. The ability to develop a "sense for quantity" is under the responsibility of a region of our brain called the parietal lobe and, particularly, of one of its indentations, the intraparietal sulcus (IPS) (see Figure 1). A rudimentary version of a "sense for quantity" develops very early in life (i.e., before schooling and even prior to the emergence of language)[7], and is progressively refined throughout development[8]. This ability is one of the precursors of the development of successful numerical and arithmetical skills[9,10].

Besides knowing and understanding quantities, it is also necessary that our brain properly decodes the symbols *3* and *4*. When these are written, they are decoded by a region in the visual cortex, in the back of our brain. This region is highly specialized to decode complex shapes, such as number-symbols, and also letters, faces, or complex objects[11–13]. It is called the *fusiform gyrus* (FG) (see Figure 1).

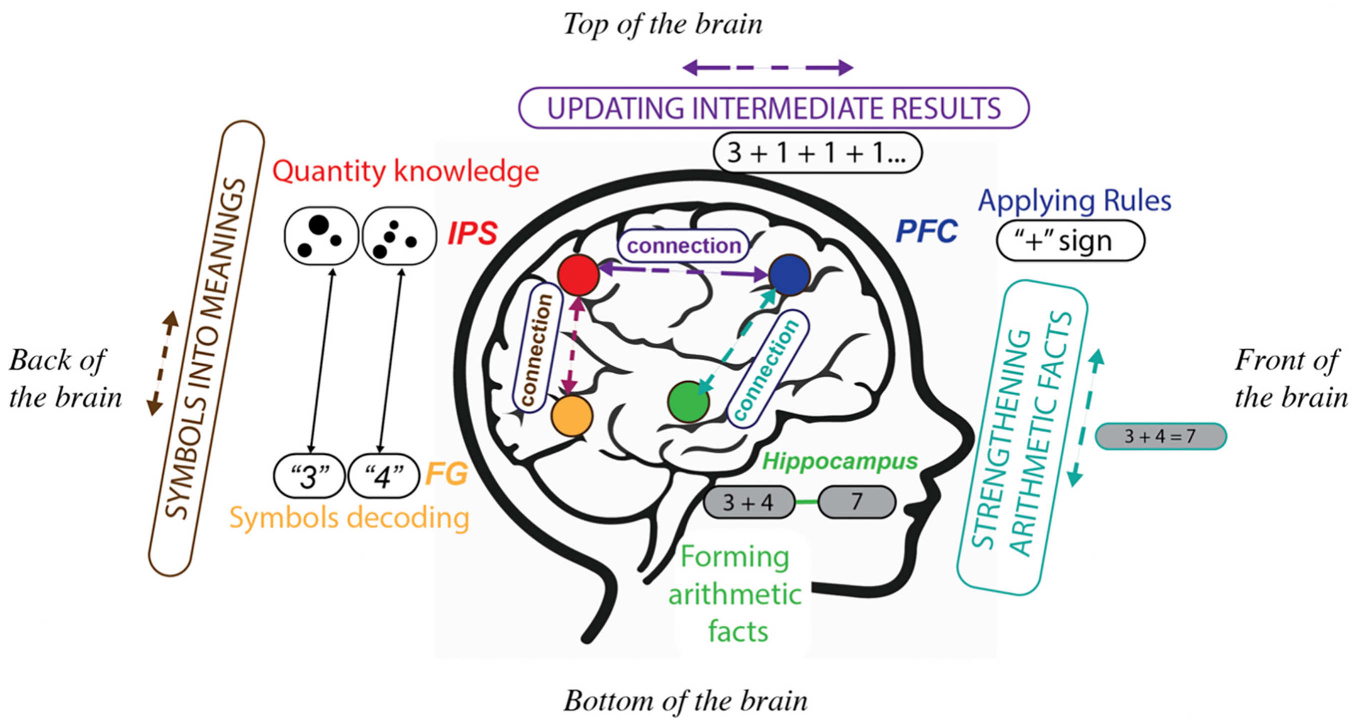


Figure 1. Multiple brain regions are involved in successful arithmetic learning.

Next, it is crucial that knowledge of these (arbitrarily defined) cultural visual symbols is appropriately associated with our knowledge of quantity: the quantity of *three* needs to be associated with the symbol *3*, not *4*. This is likely achieved by the development of appropriate connections between the IPS and the FG as part of a general pathway for translating symbols into meanings similar to—or very likely overlapping with—the one we use when learning to read[14].

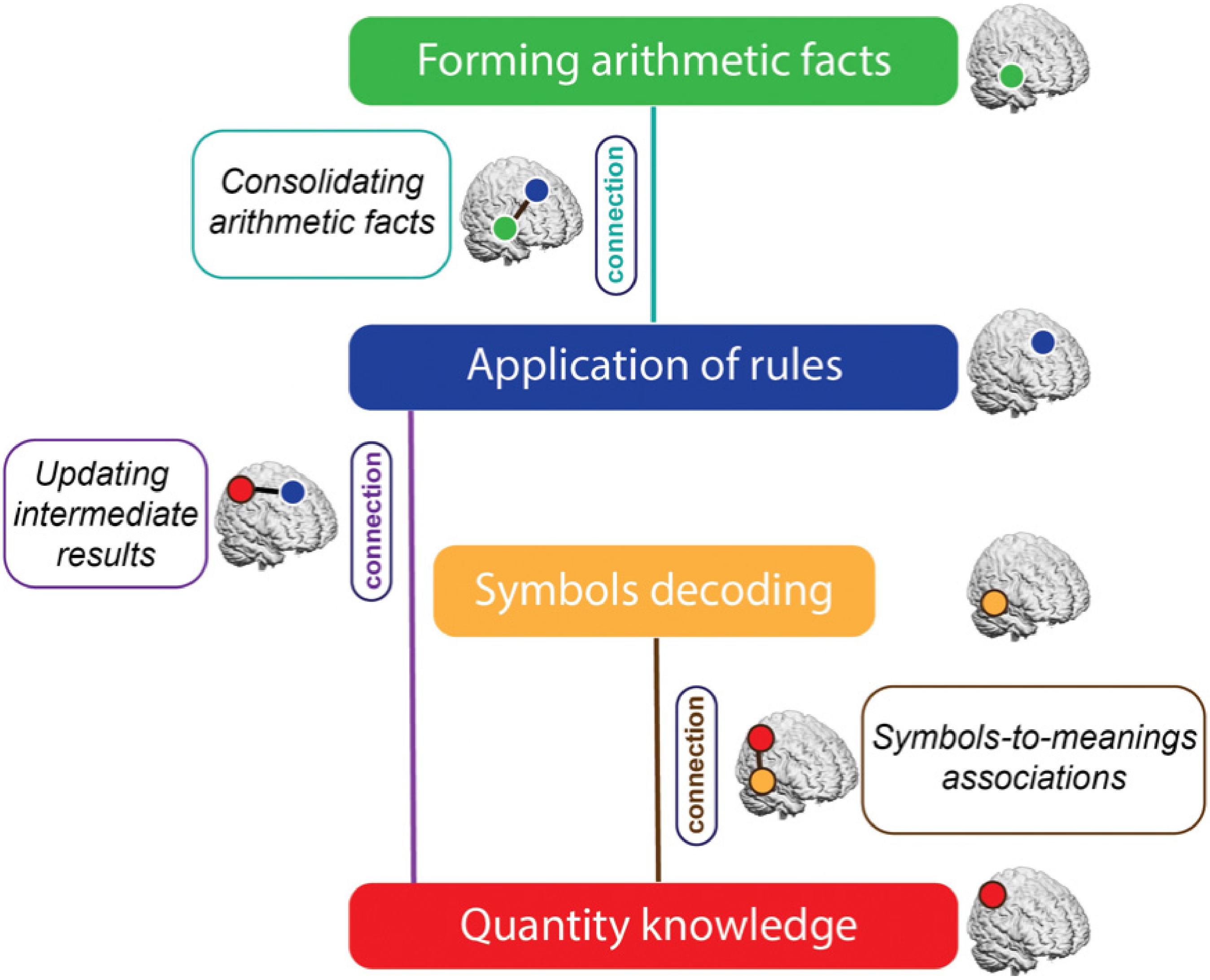


Figure 2. Disruptions at one or multiple levels of the "brain hierarchy" for arithmetic learning can lead to DD.

Once our brain establishes the appropriate link between symbols (e.g., *3*) and their meanings (e.g., *threeness*), it still needs to add quantities together. This is achieved slowly and with the help of regions in the front of the brain referred to as the *prefrontal cortex* (PFC) (see Figure 1). The PFC supports a class of complex abilities called *executive functions* (EFs). EFs refer to all those skills that help us perform goal-directed and purposeful actions/behaviours, including the ability to plan, the ability to adequately apply rules, as well as the ability to successfully hold and update information "on the fly." The latter is called *working memory* (WM) and it is achieved through the support of connections between the PFC and the IPS[15]. During arithmetical learning, WM is important to create short-term "slots" to hold (and manipulate) intermediate results over several seconds (e.g., during repeated/incremental counting).

When counting on from 3 to 7 to solve the problem "*3+4*" an association is then slowly, yet dynamically, formed between the correct solution *7* and its addends (*3* and *4*). This is aided by another memory-formation system residing in a small, curved formation in the brain called the *hippocampus* (see Figure 1). After many repetitions, and through "cross talks" between the hippocampus and the PFC, the association between *3+4* and *7* gets consolidated. At this point, our brain is finally able to directly retrieve the answer from memory when presented with the problem, and no longer needs the aid of effortful WM resources (see Figure 1).

A "disruption" at any (or multiple) level(s) of this hierarchical cascade of mental computations required to perform even simple arithmetic operations can lead to DD (see Figure 2). Notably, "perturbations" occurring at core levels (i.e., quantity knowledge, symbols' decoding) can progressively and negatively impact subsequent levels of knowledge-acquisition, and they represent the most severe forms of DD[16]. Being able to identify at which level brain systems go "off course" is critical for appropriate diagnosis and for targeting interventions.

Can neuroscience help diagnose developmental dyscalculia?

Can neuroscience help us elucidate if and how different brain systems go "off course" during arithmetic learning? Over the years, the research community has made significant progress in defining and characterizing specific learning disabilities (SLD), including DD—with important implications for struggling learners. Notably, at least in some communities and school settings, being bad at math is no longer regarded as "not trying hard enough," or "not being intelligent enough." At present, several countries have implemented some ad hoc approaches to support individuals with SLD more effectively. These include, for example, the *Individuals with Disabilities Education Act (IDEA)* in the USA, the *SEND Code of Practice 2014* in England, and *Law 104* in Italy—all of which formally include DD as a SLD. Yet, inasmuch as these actions help to raise awareness on the condition, the path to truly promote DD learners' trajectories is still in its infancy.

I argue here that neuroscience can help accelerate these efforts.

The most problematic aspect has been that, up until recently, the signs of DD were essentially invisible. Fortunately, advancements in neuroscience theories and tools (see Figure 3) have the potential to provide ad hoc, objective measures of atypical learning, including DD. By refining our understanding of how our brain successfully acquires mathematics (see Figure 1), we can develop quantifiable indices to help characterize how, and at which level, the brains of children (and adults) with DD go "off course." This is the concept of *biomarkers*, which allow unveiling of the "physical signs" of DD, similar to any other medical test.

For example, brain architecture irregularities (i.e., diminished levels of grey matter cells) have been identified in and around the IPS in children and adolescents with DD[17,18]. Even more importantly, it has been shown that, when children with DD are asked to compare quantities and numbers (i.e., which one is greater? *3* or *4*?), they show differential engagement (i.e., different brain activity) of the IPS compared to their peers without DD[19,20]. Furthermore, when children with DD are asked to verify the validity of simple arithmetic problems (e.g., *3+4 =7*?) they take longer, and tend to engage the IPS, the PFC, and the FG (see Figure 1) much more than their peers without DD[21]. This suggests that their brains have to "work harder" when solving the task. The cross talk between the IPS and PFC (i.e., brain connectivity) has also been shown to be functioning suboptimally in DD[22].

Figure 3. Magnetic resonance imaging (MRI) scanning setup. MRI allows measurement of brain properties in vivo, and it is minimally invasive. It can detect architectural brain irregularities (e.g., diminished levels of grey matter cells), or metabolic imbalances (e.g., greater or lower amount of cerebral blood flow). The latter can help infer whether one or multiple brain regions are recruited more (or less) during a particular task. *[Picture source: the Stanford Cognitive & Systems Neuroscience Lab]*

Biomarkers can also help us assess—more objectively than any standard cognitive test—whether compensatory strategies/mechanisms are taking place, or whether the expected brain regions are appropriately recruited during math problem-solving in atypical/struggling learners. Moreover, biomarkers could help assess the effects of an intervention. It is possible, for example, that after an intervention, performance improves but brain systems are still struggling[21], and no cognitive test can attest to that.

Yet, some of these biomarkers are still very expensive. Most importantly, they are still not as precise as other medical tests nor standardised, making it difficult to justify their implementation at a large scale. This is mostly due to research teams using slightly different measuring parameters and tasks.

When looking at math learning, the neuroscience community is also missing *longitudinal studies* of normal development in which the same (non-DD) child is assessed several times as they grow up. Critically, these multi-time-point studies should measure various brain properties simultaneously (e.g., brain activity, brain architecture, brain connectivity). This type of research could help us trace a more accurate trajectory of the various brain regions and mechanisms involved in successful math learning at each time of development. This will, in turn, allow us to properly take into account individual differences in math learning on the basis of better—and more precise—"developmental brain norms."

A promising approach may also be to look at early biomarkers of sensitivity towards, for example, quantity properties of a scene. Using a technique that can record electrical activity at the surface of the brain—electroencephalography (EEG)—researchers have shown that regions around the IPS of the brains of normally developing infants as young as three months are sensitive to changes in the quantity of items in sets. Notably, their electrical activity around the IPS is similar to that of 4-year-olds and even adults performing quantity discrimination tasks[23]. This is an example of how brain-based parameters can be used for early screening, and consequently, pave the way to prevention and intervention.

All in all, even if still in its infancy, neuroscience has the unique potential to provide quantifiable indices to aid our understanding of individual differences in math learning, particularly for children falling at the lower end of the distribution of abilities, such as those with DD. It is critical that this effort begins by formalizing the critical milestones that characterize brain development during successful math learning. This knowledge will in turn be able to address—more precisely and comprehensively—which regions and mechanisms are implicated in the atypical course taken by the brain in DD.

### Designing and testing intervention programs for DD

*Appropriate screening.* To create the best, most effective (and ad hoc) intervention programs for DD, it is first crucial to acknowledge individual differences in DD learners and thus be able to stratify different learning profiles. Ideally, as discussed, this step is accompanied by brain-based objective measures of the deficit: Which brain system(s) for math problem-solving is/are "disrupted" and how? (see Figure 2). Yet, note that, as discussed, appropriate biomarkers are still not available or fully implementable for DD. On the brighter side, researchers across the world are teaming up to create individualized, computerized screening measures that are based on the neuroscientific literature (see Figure 1) and can assess DD at multiple levels of knowledge acquisition.

*The science of intervention.* In order to properly evaluate the effects of an intervention, the correct implementation of an appropriate study-design is essential. This includes: (1) a "test group" (with DD) that is assigned to a given intervention-program for a given duration (e.g., N times a week for N weeks); (2) a "control group" (with an equivalent form of DD) that is assigned to a different (or placebo-like) intervention of the same duration; (3) a "pre-post design," such that performance of both groups is measured (using the same tests) before and after the intervention; and ideally, (4) two groups of non-DD children, one undergoing the same intervention as the "test group" and the other undergoing the same intervention as the "control group." It would also be advisable to foresee: (5) follow-up testing sessions in all groups to assess longevity-effects. These studies are expensive and lengthy, but absolutely necessary in order to scientifically validate the effects of an intervention program for DD.

*Testing an intervention at the performance-level and at the brain-level.* It is important that when we are testing an intervention, we evaluate it at multiple levels of analysis. For example, it is possible that even if we see an improvement in performance after a given intervention, the brain is still working harder than it should to reach that performance or, in other words, is still not behaving typically. This will imply that the given ability has not been fully remediated, with greater chances for a relapse. A recent study evaluated a comprehensive one-to-one arithmetic intervention program in a group of children with DD. It showed that two months of this program not only remediated poor performance in DD, but also induced widespread changes in their brain activity. Importantly, after the intervention, brain activity in the DD group was indistinguishable from that of a group of non-DD children, suggesting that the intervention was indeed effective[21].

*Implementation.* One-to-one intervention programs[21] are costly and hard to implement at a large scale. The advent of digital learning technologies can help in this case. Digitally-based, adaptive intervention programs can be designed around the learner, both in terms of type of ability to be remediated, as well as its severity. These programs should: (1) be developed on the basis of neuroscience findings; (2) integrate/accompany—rather than substitute—the role of the teacher/tutor; and (3) be designed to provide a pleasant learning environment (i.e., include systematic and frequent feedbacks, as well as rewards).

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