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REVIEW

Understanding Neurocognitive Developmental Disorders Can Improve Education for All

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Specific learning disabilities (SLDs) are estimated to affect up to 10% of the population, and they co-occur far more often than would be expected, given their prevalences. We need to understand the complex etiology of SLDs and their co-occurrences in order to underpin the training of teachers, school psychologists, and clinicians, so that they can reliably recognize SLDs and optimize the learning contexts for individual learners.

In the not-too-distant past, children who were unable to learn the usual school subjects to a normal level were classified as having mental retardation, or what we would now call "intellectual disability" (U.S.) or "learning disability" (UK). These labels are still sometimes applied to children with severe delays in learning to read and spell, whom we would now call dyslexic, or those with serious social difficulties, whom we would now call autistic (*1*).

Extensive research in cognitive development shows that children with normal or even superior IQs, and who clearly are not mentally retarded, can fail to reach acceptable standards in key curriculum areas, such as literacy (*2*) and numeracy (*3*). The terms intellectual or learning disability are currently reserved for those whose score on an IQ test is below 70 (the lowest 2%, approximately).

The evidence outlined in this Review presents multiple reasons why it is difficult to define neurocognitive developmental disorders. Complex genetic, brain, and cognitive processes underlying these conditions remain poorly understood.

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Throughout the Review, we refer to specific learning disabilities (SLDs), following the U.S. federal law definition of "a disorder in one or more of the basic psychological processes involved in understanding or in using language, spoken or written, that may manifest itself in an imperfect ability to listen, think, speak, read, write, spell, or to do mathematical calculations" (*4*). We apply this term to such diverse conditions as dyslexia or autistic spectrum disorder to emphasize the uncertainty about their classifications. Irrespective of definitions, SLDs are thought to affect approximately 10% of the population (Table 1) and have a profound effect on educational outcomes. Unlike learners with intellectual disability, who need at least some educational support in all curriculum areas and, in severe cases, support in daily living, those with SLDs need support mainly in those areas of specific weakness. Here we focus on just five SLDs (Table 2).

The Co-Occurrence of Specific Learning Disabilities

An additional problem for the educator is that SLDs co-occur far more often than would be expected given their prevalences (Table 1). If, for example, dyslexia and dyscalculia were entirely independent conditions, then the expected rate of co-occurrence would be the product of the base rates: i.e., 7% × 6%, or about 0.5%. However, one population-based study with these prevalences found that 23 to 49% of children in grades 2 to 4 had disabilities of both literacy and numeracy (*5*). Studies of selected samples of other SLDs also indicate a higher level of co-occurrence than that expected by chance. For example, of children with attention-deficit/hyperactivity disorder, 33 to 45% also suffer from dyslexia (*6*); and 11% from dyscalculia (*7*).

The co-occurrence of autism spectrum disorder and attention-deficit/hyperactivity disorder have also been reported, although not consistently across the age range (*8*); the occurrence of numeracy and literacy disorders in autistic spectrum disorder is roughly equivalent to that in typically developing learners (*9*).

Domain-General Explanations

Many studies have sought to explain SLDs and their co-occurrence in terms of "domain-general" cognitive capacities such as those measured by IQ tests, tests of working memory (the retention of task-relevant information for the duration of the task), or tests of processing speed. However, there are important differences in what the commonly used tests measure. For example, the widely used Wechsler IQ tests for adults and children (*10*, *11*) require knowledge of vocabulary, numbers, and arithmetic, whereas other tests require only spatial and reasoning skills (*12*). Different intelligence tests may thus give different assessments. Nevertheless, many authorities, including the U.S. Office of Education and the American Psychiatric Association, recommend using a significant discrepancy between IQ and a test of reading, mathematics, or social ability as the criterion for diagnosis of a SLD (see Table 2 for examples). This makes the diagnosis more probable for individuals of high intelligence and excludes the possibility that an individual can have both low intelligence and an SLD. In fact, SLDs may actually cause poor performance on some IQ tests. This is most obvious where the IQ test depends on reading and understanding and also a reasonable degree of numeracy (*13*).

Measures of working memory include tests of the ability to reproduce a string of digits in the presented order, whereas other tasks tap the ability to modify the contents of memory in response to current task demands. The association between working memory and SLD depends on the working memory task used and the SLD being assessed (*3*, *14*).

Core Cognitive Deficits

Given the problems with trying to explain the varieties of SLDs in terms of domain-general capacities, much research has been motivated by the postulation of core cognitive deficits that can give rise to the observed behavior. Core deficits themselves can have many causes and variable behavioral manifestations (Fig. 1).

Core Deficit in Dyslexia

At the cognitive level, a large majority of dyslexic children seem to suffer from a phonological deficit: a deficit in some aspects of the processing of speech sounds and their mental representation, although subtle visual or attention difficulties may contribute in some cases (*15*). Dyslexic symptoms depend on the regularity of the mapping between letters and sounds in alphabetic orthographies and thus will present in different ways in, for example, Italian and English, but its neurological basis is always found in areas of the brain that link letters to speech sounds (*16*).

Core Deficit in Dyscalculia

Children with dyscalculia show a core deficit in processing numerosities, which is revealed in slower and less accurate enumeration of small sets of objects and in comparing the numerosities of sets of objects or the magnitude of digits (*17*). However, good language abilities appear to be needed for the typical development of counting, calculation, and arithmetical principles (*18*).

Table 1. Estimated prevalences of five specific learning difficulties. NIH research funding for these SLDs in 2000–2009 varied widely (*1*, *32*)

SLD	Estimated prevalence (%)	NIH research funding in U.S. $1000s
Dyslexia	4–8	27,283
Dyscalculia	3.5–6.5	1,574
Attention-deficit/hyperactivity disorder	3–6	532,800
Autism spectrum disorder	1	851,270
Specific language impairment	7	28,611

Table 2. Definitions of SLDs. Adapted from (*19*, *20*). See the text for more detailed characterization of these deficits.

SLD	Definitions
Development dyslexia	Developmental disorder in learning to read, not due to impairments in general intelligence, sensory problems, emotional disturbances, or inadequate schooling.
Developmental dyscalculia	Substantial underachievement on a standardized test of arithmetic relative to the level expected, given age, education, and intelligence, which causes disruption to academic achievement or daily living.
Attention-deficit/hyperactivity disorder	Symptoms of inattention, hyperactivity, and impulsivity, such that these symptoms cause clinically significant distress or impairment in social, academic, or occupational functioning.
Autism spectrum disorder	Impairments of social interaction and communication and repetitive, stereotyped behavior.
Specific language impairment	Significant deficits in expressive or receptive language, not due to sensory or environmental deprivation, co-occur with nonverbal intelligence within the average range

Core Deficit in Attention-Deficit/ Hyperactivity Disorder

Children diagnosed with attention-deficit/hyperactivity disorder may have several core cognitive deficits, including one in attention and one in controlling, and especially inhibiting, behavior. The American Psychiatric Association distinguishes two subtypes, inattentive and hyperactive-compulsive (*19*), whereas the World Health Organization distinguishes a hyperkinetic disorder subtype from a comorbid conduct disorder subtype (*20*).

Core Deficit in Autism Spectrum Disorder

A core deficit in representing one's own and other people's thoughts and feelings is implicated in this condition, which is sometimes called a deficit in the theory of mind (*21*). As a consequence, individuals with autism have impairments in communication that depends on understanding others' intentions. However, the nonsocial aspects of autism, such as obsession with detail, are not explained by this deficit alone (*22*).

Core Deficit in Specific Language Impairment

Children diagnosed with this condition have difficulties with the meaning of words, syntax, and pragmatics, despite adequate intelligence, sensory apparatus, and exposure to language input. Specific language impairment appears to result from several core deficits, including the phonological deficit that is shared with dyslexia. The vast majority of children with this condition perform at least 1 SD below age controls, not only on comprehending texts, which will depend on understanding word meanings, grammar, and pragmatics, but also on reading aloud single words, which depends largely on the ability to map from letters onto the component sounds of words (*13*).

More generally, although core deficits frequently co-occur, they do not appear to interact. For example, children with attention-deficit/hyperactivity disorder alone performed relatively poorly on tasks requiring sustained attention, whereas children with dyslexia performed more poorly on phonological tasks; however, children with both conditions were not worse on either task (*23*). Similarly, children with both dyscalculia and dyslexia were no worse on tests of numerosity processing and phonological processing than those with just one condition (*3*, *24*).

Neurological Basis of SLDs

The representative but not exhaustive evidence presented in Table 3 suggests that each SLD is associated with an abnormality in a distinct neural network. The neuroanatomical differences between learners with SLDs and typically developing learners usually have been found in magnetic resonance imaging (MRI) studies. However, it should be noted that important differ-

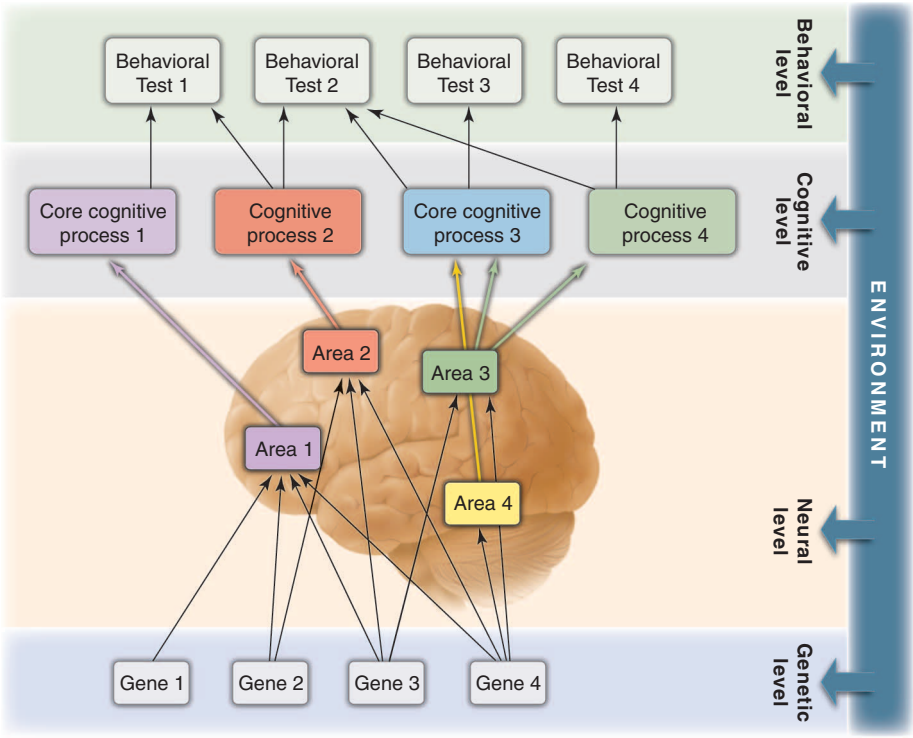

Fig. 1. Networks of interaction. Schematic model of the relationships among levels of explanation—genetic, neural, cognitive, and behavioral—following the causal modeling framework (*34*). There can be many-one, one-many, many-many, and one-one relationships between levels. A domain-general cognitive process and a domain-specific core cognitive process can have effects on more than one behavioral test, and performance on a behavioral test may be affected by more than one cognitive process. Moreover, one cognitive process may depend on another (e.g., memory on attention), and one behavior may causally affect another (e.g., poor reading may impair mathematical problem solving).

Table 3. Typical results for structural brain imaging in which probands with an SLD differ significantly from typically developing controls.

	Structural difference with controls	Subjects
Dyslexia (*39*)	Decreased gray matter density in left midtemporal gyrus and increased density in mid-posttemporal gryus Decreased white matter volume in left arcuate fasciculus	10 Italian, 11 French, 11 English probands 9 Italian, 12 French, 11 English controls
Dyscalculia (*40*)	Decreased gray matter density in left intraparietal sulcus	12 probands, 12 controls
Attention-deficit/hyperactivity disorder (*41*, *42*)	1. Decreased overall brain volume and cortical thickness 2. Decreased volume of anterior cingulate cortex 3. Decreased volume of frontal cortex 4. Cerebellum	1. 59 probands, 80 controls. 2. to 4. Review and meta-analysis
Autism spectrum disorder (*43*)	Greater total brain volume and grey matter volume throughout life span, most prominently in frontal lobe Greater prepuberty white matter volume	Review and meta-analysis
Specific language impairment (*44*)	Abnormal perisylvian asymmetry	20 probands, 12 controls

ences may not show up in the structure or activity of the brain as revealed by MRI, such as neurotransmitter dopamine abnormalities in attention-deficit/hyperactivity disorder (*25*).

Nevertheless, a single neurophysiological cause may affect distinct regions. For example, some individuals are prone to abnormal neuronal migration in brain development (ectopias). Such abnormal neuronal migration has been associated with dyslexia (*26*). However, it is not yet known whether the genetic anomalies that give rise to ectopias in dyslexia may also cause them in other brain regions, thus increasing the risk of other SLDs.

Genetic Basis of SLDs

Most recent genetic work on the etiology of developmental disorders and their co-occurrence has been conducted using large unselected samples, in which disability is defined and investigated as the low end of ability. Probands (affected individuals) in such studies are selected as extremes of the distribution in any trait of interest in a representative sample. Such research consistently found moderate to high heritability for all cognitive and behavioral traits (*27*). Research suggests that all cognitive traits are polygenic: influenced by many genes with small effects. On this account, a disorder will be affected by many genes (*27*). In addition, there is pleiotropy; that is, the same genes may affect multiple traits implicated in diverse cognitive processes, and one gene may depend on the activity of another gene (a process called epistasis).

Twin studies report genetic correlations of 0.2 to 0.7 among SLDs, indicating the extent to which the same genes are involved in the different conditions. These studies also show that shared environments, such as maternal stressful life events, contribute to comorbidity, especially for autistic traits and attention-deficit behaviors (*28*).

Nevertheless, a substantial proportion of genetic variance can also be associated with a single domain. For example, in one large twin study of 7-year-olds, some 30% of genetic variance was specific to mathematics (*29*). However, it remains unknown whether the co-occurrence of reading, math, and other cognitive domains is due to a small set of foundational skills, influenced by both genetics and/or shared environment (see Fig. 2 for an illustration).

Most genes found so far to be associated with cognition seem to work throughout the

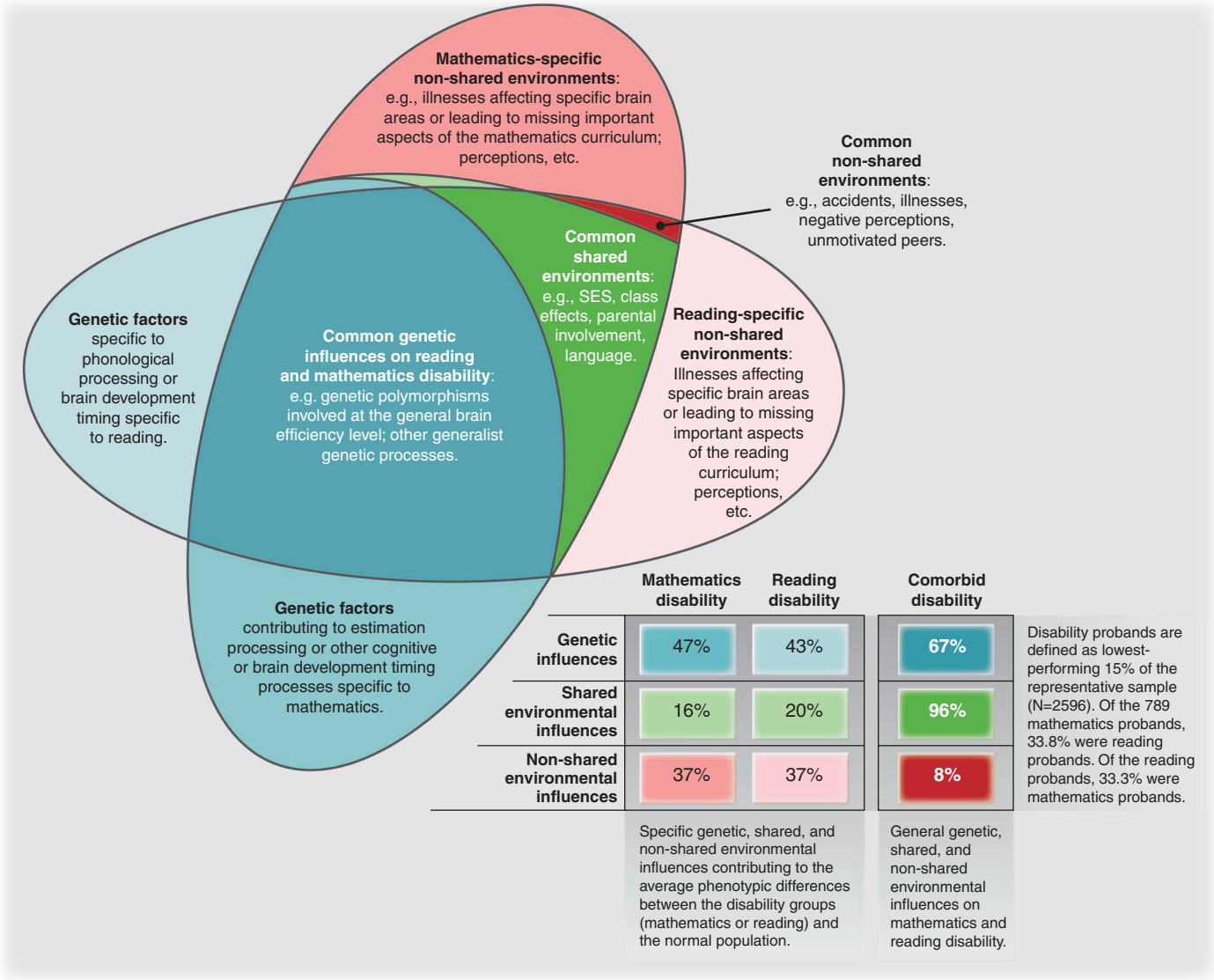

Fig. 2. Etiology of the overlap and specificity of mathematical and reading disabilities. Based on the data from a large-scale twin study (*35*).

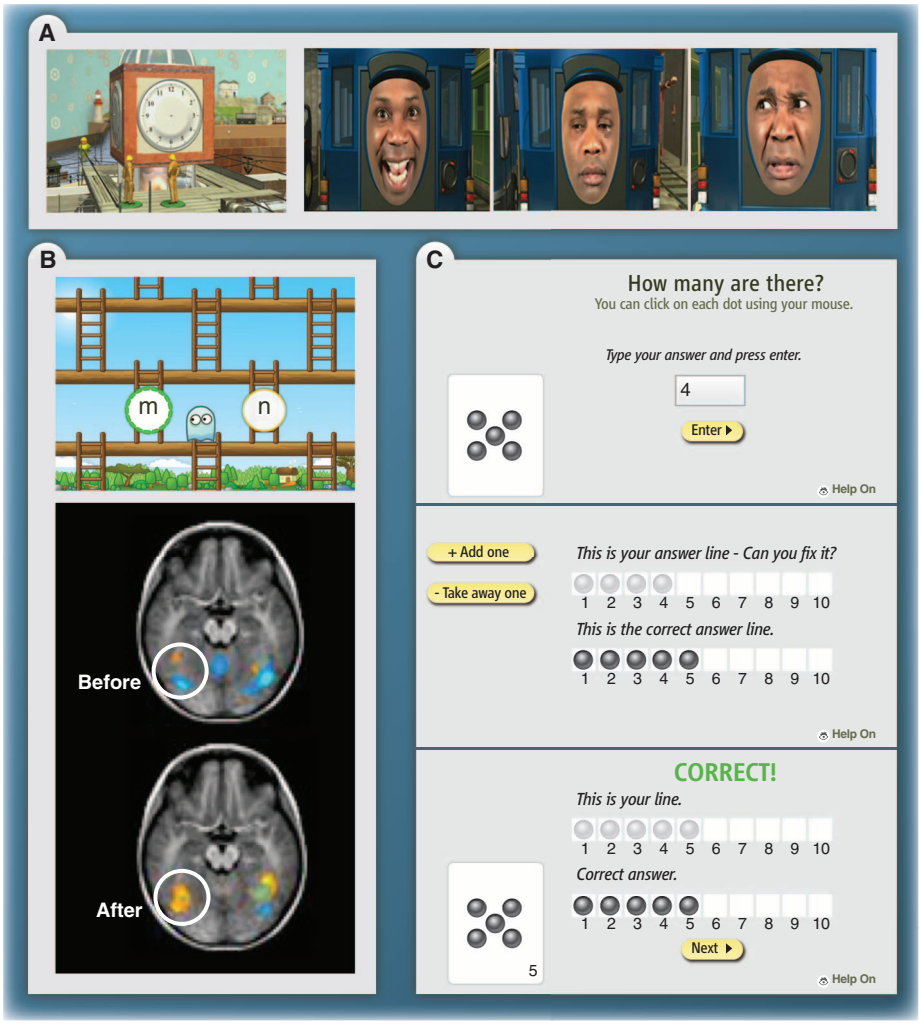

Fig. 3. Examples of adaptive games for SLDs. (**A**) A still frame from a game to help young autistic spectrum learners to recognize facial emotions. The game uses Transporters: locomotives and cable cars with human faces designed to prevent the learner from avoiding faces (*36*). (**B**) Images from Graphogame, a method for teaching early readers and dyslexics letter-sound correspondences. The effects on the brain of 3 hours of training are shown in the brain images (*37*). (**C**) An edited sequence of events in the Dots2Track game. (Top) The learner selects a digit corresponding to the number of black dots on the screen. (Middle) Here the answer is incorrect, so the correct number of black dots is counted onto the lower track along with spoken digits, and the response in gray dots is counted down onto the upper line. The learner then has the opportunity to construct the correct answer by adding or taking away a dot until the correct answer is achieved (bottom). The constructive process promotes better learning (*38*).

Grand Challenges

Develop an understanding of how individual differences in brain development interact with formal education. Investigate how cognitive processes, their neural basis, and their genetic etiology influence the individual's experience of his or her learning environment.

Adapt learning pathways to individual needs. Each child has a unique cognitive and genetic profile. The educational system should be able to monitor and adapt to the learner's current repertoire of skills and knowledge. A promising approach involves the development of technology-enhanced learning applications that are capable of adapting to individual needs for each of the basic disciplines.

distribution, explaining variation in the normal range as well as discriminating probands from the "normal population." Multiple gene variants have been associated with dyslexia (*30*). However, the associated physiological mechanisms, involving neuronal migration and growth, seem paradoxically general, rather than specific to reading.

Although many genetic abnormalities, such as Down or Williams syndromes affect many aspects of cognition, others can have specific cognitive effects (Fig. 3). Turner's syndrome, for example, is linked with dyscalculia but not with any other SLD (*31*).

Educational Implications

Although neurodevelopmental disabilities are congenital, they are rarely identified until relatively late in childhood, if at all, because specialized assessments are difficult to access (*1*) and teachers and parents are often poorly informed about them. Moreover, because of the high rates of co-occurrence, it is likely that an unassessed SLD will be treated as the consequence of the assessed SLD. For example, the dyslexia in a child assessed with attention-deficit/hyperactivity disorder could be assumed to result from that condition and therefore be treated pharmaceutically (e.g., with methylphenidate) but without the specialized help that learners with dyslexia need. Similarly, for a child assessed with dyslexia who also has dyscalculia, a learning program designed to treat the reading disability alone may be implemented. This may be particularly true when one condition is more spectacular or obvious than the other, or indeed when one SLD is more intensively researched than another. For example, National Institutes of Health (NIH) research funding in 2008–2009 for autistic spectrum disorder was 31 times greater than for dyslexia and 540 times greater than for dyscalculia [see the analysis in (*32*), based on data from http://projectreporter.nih.gov/reporter.cfm].

To meet these grand challenges, two important systemic changes will need to take place. First, research into the developmental trajectories of neurocognitive disorders is desperately needed, especially those leading to specific language impairment, dyslexia, and dyscalculia, which are relatively neglected in terms of research funding, despite their impact on the life chances of affected learners (*33*). But it is also vital to study the even more neglected co-occurrences among SLDs and the educational consequences of co-occurrence. Are the effects of two SLDs additive or multiplicative? What is the etiology of these effects? Better understanding of the etiology will also help with individualizing education for all learners. Second, and informed by the first, teachers, school psychologists, and clinicians need to be trained to identify and understand SLDs and to design learning pathways for each individual sufferer.

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REVIEW

Physical and Virtual Laboratories in Science and Engineering Education

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The world needs young people who are skillful in and enthusiastic about science and who view science as their future career field. Ensuring that we will have such young people requires initiatives that engage students in interesting and motivating science experiences. Today, students can investigate scientific phenomena using the tools, data collection techniques, models, and theories of science in physical laboratories that support interactions with the material world or in virtual laboratories that take advantage of simulations. Here, we review a selection of the literature to contrast the value of physical and virtual investigations and to offer recommendations for combining the two to strengthen science learning.

Policy-makers worldwide recommend including scientific investigations in courses for students of all ages (*1*, *2*). Research shows advantages for science inquiry learning where students conduct investigations compared with typical instruction featuring lectures or teacher demonstrations (*3*, *4*). Investigations provide opportunities for students to interact directly with the material world using the tools, data collection techniques, models, and theories of science (*1*). Physical, hands-on investigations typically fill this need, but computer technologies now offer virtual laboratories where investigations involve simulated material and apparatus. The value of physical laboratories for science learning is generally recognized (*1*), but the value of virtual, simulated alternatives for hands-on physical laboratories is contested (*5*). We explore whether this hesitation concerning virtual laboratories is justified.

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Affordances of Physical and Virtual Laboratories

Physical and virtual laboratories can achieve similar objectives, such as exploring the nature of science, developing team work abilities, cultivating interest in science, promoting conceptual understanding, and developing inquiry skills, yet they also have specific affordances (*1*). Using physical equipment, students can develop practical laboratory skills, including troubleshooting of machinery, and can experience the challenges many scientists face when planning experiments that require careful setup of equipment and observations over long time spans. A related affordance of physical laboratories is that they can take advantage of tactile information that, according to theories of embodied cognition, fosters development of conceptual knowledge [see e.g., (*6*, *7*)].

An important affordance of virtual laboratories is that reality can be adapted. Designers of virtual experiments can simplify learning by highlighting salient information and removing confusing details (*8*), or they can modify model characteristics, such as the time scale, that make the interpretation of certain phenomena easier (*9*). Students can conduct experiments about unobservable phenomena, such as chemical reactions, thermodynamics, or electricity (*10*–*13*). For example, students can vary the properties