CHAPTER 5

Cognitive Processes, Neuroscience, and Learning Disabilities

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The National Center for Learning Disabilities (NCLD) estimates that approximately 20% of children in the United States have learning and attention difficulties that could be classified as learning disabilities (Horowitz et al., 2017). Put another way, according to the Learning Disabilities Association of America and the National Center for Education Statistics, approximately 2.3 million students have learning disabilities and receive services in school (Learning Disabilities Association of America, n.d.-a). While these numbers may seem high at first glance, they are actually more likely to be underestimates rather than overestimates; children of racial or ethnic minorities are consistently less likely than White children to be identified as having learning disabilities (Morgan et al., 2015). The Individuals with Disabilities Education Act (IDEA) defines a learning disability as "a disorder in one or more of the basic psychological processes involved in understanding or in using language, spoken or written, which disorder may manifest itself in the imperfect ability to listen, think, speak, read, write, spell, or do mathematical calculations" (IDEA, 2004). These disorders are typically caused by genetic and/or neurobiological factors that alter brain function (Learning Disabilities Association of America, n.d.-b). Included in IDEA's definition of learning disabilities are conditions such as brain injury and dyslexia; excluded from this definition are conditions such as intellectual disabilities or mental health conditions (IDEA, 2004). To be classified as having a learning disability, students must have at least average intelligence (Learning Disabilities Association of America, n.d.-b).

Reading

The most common learning disability is a reading disability; approximately 80% of children who have at least one learning disability also exhibit difficulties with reading (Shaywitz, 2003). Put another way, while they may not all receive a diagnosis, it has been estimated that approximately 16% of students struggle to at least learn to read (Shaywitz et al., 1992). “Reading disability” is synonymous with other similar terms such as “reading difficulty,” “reading impairment,” and “reading disorder.” “Reading disability” is also an umbrella term that encompasses several different types of reading difficulties, including difficulties with sounding out and recognizing words and difficulties with reading comprehension (McArthur & Castles, 2017).

The effects of reading disabilities on personal and public health make the importance of the study of typical and impaired reading development strikingly apparent. Students who struggle to learn to read, failing to achieve their first major milestone in school, are at risk for severe long-term consequences, including school dropout (Daniel et al., 2006), attempted suicide (Daniel et al., 2006), incarceration (Christle & Yell, 2008), anxiety and depression (Carroll et al., 2005), and/or low self-concept (McArthur et al., 2016) compared to their peers reading at grade level (McArthur & Castles, 2017). On a larger scale, these adverse outcomes cost society money; in our present society, special education, public healthcare, incarceration, and underemployment necessitate the use of resources such as extra special education teachers and equipment and systems such as the Supplemental Nutrition Assistance Program and Medicaid, both of which use taxpayer dollars (Center on Budget and Priority Policies, 2022).

Earlier identification of students with reading disabilities and earlier remediation of such disabilities would help lessen the need for these resources and, therefore, lower their costs. Indeed, it is important to study reading and, moreover, reading disabilities in hopes of eventually remediating these disabilities, ultimately alleviating these adverse consequences.

Reading Cognition

After decades of research, reading and reading disabilities are relatively well understood (Fletcher et al., 2007). A framework through which reading is commonly studied and explained (Duke & Cartwright, 2021) is the Simple View of Reading (SVR; Gough & Tunmer, 1986; Hoover & Gough, 1990). The original version of SVR posits that Reading (R), or the comprehension of written text, is the product of two independent, sequential processes: Decoding (D) and Listening Comprehension (LC) (Gough & Tunmer, 1986; Hoover & Gough, 1990). Decoding (D) is defined as the ability to “read isolated words quickly, accurately, and silently” using “letter-sound correspondence rules” (Gough & Tunmer, 1986). Listening comprehension (LC) is the ability to understand the meanings of words (Gough & Tunmer, 1986; Hoover & Gough, 1990). The original version of the SVR can be simplified and reduced to one small but extremely meaningful equation: $D \times LC = R$ (Decoding × Listening Comprehension = Reading). As the product of anything times zero equals zero, this equation involving a product implies that if a student does not have Decoding and/or Listening Comprehension, making at least one of those processes 0, that student is unable to Read.

The original version of the SVR (Gough & Tunmer, 1986) has undergone several revisions and updates in the decades since it was first published. The most recently updated version of the SVR, published in 2020, retains the basic equation but renames the two processes to more appropriately represent their functions (Hoover & Tunmer, 2020). This new version of the SVR broadens "decoding" to "word recognition" and "listening comprehension" to "language comprehension" (Hoover & Tunmer, 2020).

Extensive cognitive research of reading supports and validates the SVR (e.g., Aaron et al., 2008; Carver, 1997, 2003; Catts et al., 2006; Curtis, 1980; Cutting & Scarborough, 2006; Francis et al., 2005; Goff et al., 2005; Joshi et al., 1998; Lervåg et al., 2018; Protopapas et al., 2012; Sabatini et al., 2010; Shankweiler et al., 1999; Vellutino et al., 2007).[1] Neurobiological research also supports the SVR (e.g., Cutting et al., 2013; Hudson et al., 2016; Landi et al., 2013). In the next few sections, we briefly review literature on the cognition and neurobiological correlates of word recognition and reading comprehension and these processes' associated deficits.

Word Recognition Deficits (Dyslexia)

Impairments in word-level processes, such as word recognition and decoding, comprise a common subtype of reading disability: dyslexia. According to Lyon, Shaywitz, Shaywitz, and other members of the International Dyslexia Association, "dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and by poor spelling and decoding abilities" (Lyon et al., 2003, p. 2), despite at least average intelligence and at least adequate reading instruction (Norton et al., 2015). The fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5) defines dyslexia as a "specific learning disorder" "with impairment in reading," specifically impairments in word reading accuracy, reading rate, and/or reading fluency (American Psychiatric Association, 2013). It has been estimated that approximately 5–17% of all children and adults in the United States fit these diagnostic criteria (Shaywitz, 2003). Individuals who struggle with word-level processing/dyslexia tend to struggle with those words because they actually have underlying impairments in phonological awareness, or "the conscious ability to detect and manipulate sounds of language" (Marinac, 2008, p. 8; Liberman & Shankweiler, 1985; Wagner & Torgesen, 1987). Phonological deficits contribute to word-level struggles (Snowling & Melby-Lervåg, 2016) because if individuals struggle to segment phonemes in a word, they will also experience difficulty mapping these phonemes onto letters/letter combinations. Then, if individuals struggle

[1]Of note, there are many other reading frameworks and theoretical models of discourse processing that are richly developed in the cognitive literature (e.g., Cromley & Azevedo, 2007; Gernsbacher & Faust, 1991; Kintsch, 1988; McKenna & Stahl, 2015; Perfetti, 1999; van den Broek et al., 1999). However, given these other models' relatively limited translation to the neurobiological literature to date, in this chapter, we confine our discussion of reading to the SVR.

to sound out words, they will struggle to read words and eventually commit them to memory as sight words (Harrison & Stewart, 2019).

Word-level impairments can understandably significantly prohibit children's reading development, therefore causing these children to fall behind their peers in terms of their reading abilities. Then, by virtue of being unable to read at grade level, these children also fall behind their peers in terms of their academic content knowledge. Fortunately, there are evidence-based interventions targeting word-level impairments that are beneficial for most children who have dyslexia (see the U.S. Institute of Education Sciences' What Works Clearinghouse for evaluation of evidence-based programs).

Comprehension Deficits (Specific Reading Comprehension Disorder)

Some individuals struggle to understand the meaning of texts they have read, including making inferences and creating mental models of text. This lack of understanding can be independent of or in addition to lower word-level deficits. Individuals who possess at least average word-level skills and at least average intelligence and have been provided with at least adequate reading instruction, but still struggle to comprehend the texts they read, are likely to fit the diagnostic criteria for Specific Reading Comprehension Disorder, or S-RCD (Nation & Snowling, 1997, 1998; Oakhill et al., 1986; Spencer et al., 2014; Stothard & Hulme, 1995; Yuill & Oakhill, 1991).

The DSM-5 defines S-RCD as a "specific learning disorder" "with impairment in reading," specifically in reading comprehension (without word reading accuracy noted as impaired) (American Psychiatric Association, 2013). It has been estimated that up to 10% of children and adults have S-RCD (Catts et al., 2003; Landi, 2010; Nation & Snowling, 1998; Stothard & Hulme, 1995; Yuill & Oakhill, 1991). While S-RCD is relatively prominent in the population, it is relatively understudied, especially when compared to word-level deficits.

However, behavioral studies have revealed that individuals with S-RCD exhibit deficits in oral and written language comprehension, which contribute to their deficits in reading comprehension (Catts et al., 2006; Hulme & Snowling, 2011). More specifically, individuals with S-RCD tend to exhibit deficits in vocabulary (Cain & Oakhill, 2006; Henderson et al., 2013), semantic processing but not phonological processing (Nation et al., 2001), grammar (Goff et al., 2005; Tong et al., 2014), and higher-level language skills such as knowledge of text structure (Cain et al., 2004), inference making (Cain & Oakhill, 1999; Oakhill & Cain, 2000, 2012), and comprehension monitoring (Ehrlich et al., 1999; Oakhill et al., 2005).

That being said, the level of reading comprehension that individuals with S-RCD exhibit is lower than the level of reading comprehension they should be at, as predicted by their oral language skills. This discrepancy in reading comprehension abilities suggests that S-RCD is linked to weaknesses in other areas beyond oral language (Spencer & Wagner, 2018). Additional deficits beyond oral language have been identified in individuals with S-RCD. For example, children with S-RCD tend to also exhibit deficits in executive function (Locascio et al., 2010), suggesting that S-RCD may result from a combination of deficits in both oral language and executive function processes (and possibly other processes, too).

Discourse-level impairments can understandably significantly prohibit children's reading development, therefore causing these children to fall behind their peers in terms of their reading abilities. Then, by virtue of being unable to read and understand at grade level, these children also fall behind their peers in terms of their academic content knowledge. Fortunately, there are evidence-based interventions targeting comprehension impairments that benefit children with S-RCD (Clarke et al., 2010; Hulme & Snowling, 2011).

Regardless of their specific diagnosis, any student with a reading disability requires a timely and appropriate intervention. The longer students with reading disabilities struggle without diagnosis and intervention, the more they fall behind their peers, and the more they must learn and master in order to catch up to grade-level reading ability and grade-level academic content knowledge (Foorman et al., 1997; Fuchs et al., 2014).

Neurobiological Correlates of Reading and Reading Disabilities

Word Recognition

Complementing the large body of research on the cognition of reading, much work has been done to try to understand the neurobiological correlates of reading. The basic neurobiological model of skilled reading proposes the involvement of three major brain areas: (1) the left ventral occipito–temporal region, (2) the left dorsal temporo–parietal region, and (3) the left inferior frontal region (Black et al., 2017; Dehaene et al., 2010; Pugh et al., 2001; Richlan, 2012). The left ventral occipito–temporal region contains the putative "visual word form area" (VWFA). This region is involved in the automatic visual processing of words (McCandliss et al., 2003) and displays a striking preference for processing words and legal pseudowords as compared to illegal pseudowords or other stimuli (Ben-Shachar et al., 2007; Cohen et al., 2002; Cutting et al., 2013; Pammer et al., 2004; Price et al., 1996; Vinckier et al., 2007). The left temporo–parietal region is thought to be involved in the integration of written words and auditory speech sounds (Gabrieli, 2009). The left inferior frontal region has been linked to many aspects of reading, including verbal working memory, phonological and semantic processing, silent reading, and speech planning (Fiez & Petersen, 1998; Poldrack et al., 1999; Price, 2012). While this broad tripartite model has some utility, reading is a complex process that requires the recruitment and coordination of more than just these three broad regions. Using neuroimaging techniques, especially functional MRI, researchers have investigated specific functions of subregions within these three broad regions, resulting in more refined models of word reading (see Kearns et al., 2019). For example, Kearns and colleagues propose that within the left temporo–parietal region, the supramarginal gyrus (SMG) is involved in the translation of decoded written words to auditory speech sounds, or phonemes, while the angular gyrus (AG) is involved in semantic processing, or processing meaning of single words (Kearns et al., 2019).

Word Recognition Deficits (Dyslexia)

With some exceptions, individuals with word recognition deficits generally exhibit reduced functional activation in many regions within the reading network (D'Mello & Gabrieli, 2018). Evidence also suggests that individuals with dyslexia demonstrate greater functional activation in right hemisphere brain regions, possibly indicating use of compensatory strategies for reading (e.g., Grigorenko, 2001; Joseph et al., 2001; Pugh et al., 2008; Waldie, 2002; Waldie et al., 2013). Individuals with dyslexia also tend to exhibit structural brain differences, but those differences will not be discussed in this chapter.

More specifically, compared to that of typical readers, the left occipito–temporal region is underactivated in individuals with dyslexia when processing words (Pugh et al., 2001; Richlan et al., 2009) and other nonreading stimuli such as strings of letters, digits, pseudoletters, or symbols (Lobier & Valdois, 2015). Similarly, individuals with dyslexia tend to show underactivation in the left temporo–parietal cortex during tasks involving phonological processing (Temple et al., 2001), thus supporting the supposition that the temporo–parietal cortex is important for multimodal grapheme–phoneme integration. Compared to the robust findings in the left occipito–temporal cortex and the left temporo–parietal cortex, findings in the left inferior frontal region are rather mixed. As expected, some studies have found decreased activation in the left inferior frontal region in individuals with dyslexia (Landi, 2010; Wimmer et al., 2010). However, other studies have unexpectedly found increased activation in the left inferior frontal region (Hoeft et al., 2007; Shaywitz et al., 1998). This increased activation is hypothesized to reflect the use of compensatory mechanisms and/or an overall increased effort exerted while reading or engaging in reading-related tasks (Hoeft et al., 2007; Price, 2012).

Comprehension

Fewer studies have been conducted beyond word-level reading in developing and/or impaired readers. However, the relatively comprehensive adult literature (e.g., Horowitz-Kraus et al., 2014; Johns et al., 2008; Robertson et al., 2000; Ryherd et al., 2018; Schmithorst et al., 2006; Walenski et al., 2019), along with some studies in developing and/or impaired readers (e.g., Aboud et al., 2016, 2019; Rimrodt et al., 2010; Wang et al., 2020), reveals that comprehension of more complex written material, such as sentences and passages, involves the recruitment and coordination of more widespread and bilateral brain regions. These regions include bilateral superior temporal gyrus (STG), bilateral middle temporal gyrus (MTG), bilateral anterior temporal pole, left AG, and medial structures, such as the ventral medial prefrontal cortex (Horowitz-Kraus et al., 2014; Johns et al., 2008; Robertson et al., 2000; Ryherd et al., 2018; Schmithorst et al., 2006; Wang et al., 2020; Yang et al., 2019). While a comprehensive overview of all the processes involved in comprehension is too complex for the current chapter, understanding neurobiological processes associated with S-RCD sheds light on the neurobiological processes involved in comprehension.

Comprehension Deficits (Specific Reading Comprehension Disorder)

Studies investigating the neurobiological processes associated with reading comprehension in children are relatively sparse. Contributing to this paucity is the use of single-word tasks, instead of sentences or lengthier passages, in most neuroimaging studies investigating reading comprehension (Roe et al., 2018). Furthermore, neuroimaging studies that specifically focus on the S-RCD diagnosis are even fewer (Landi & Ryherd, 2017). However, the studies that do exist support the hypothesis that S-RCD involves intact decoding but weaknesses in comprehension (Cutting et al., 2013; Landi & Perfetti, 2007; Landi & Ryherd, 2017). Here, we elaborate on functional neuroimaging findings linked to S-RCD.

Findings from a functional neuroimaging study conducted by Cutting and colleagues (2013) demonstrate that when reading single words, adolescents with S-RCD exhibit similar patterns of activation to typically reading peers, distinct from peers with dyslexia, in occipital–temporal regions (Cutting et al., 2013). The similarities and differences in activation patterns observed support the behavioral observations that individuals with S-RCD have intact decoding and grapheme–phoneme integration abilities. Additionally, in this study, the presence of S-RCD was linked to context-dependent functional coupling-by-reading group interaction anomaly in the left inferior frontal gyrus. In other words, activity in the left inferior frontal gyrus covaried to a greater extent with activity in the hippocampal, parahippocampal, and prefrontal areas in adolescents with S-RCD than typical readers when reading low-frequency words. This pattern suggests that individuals with S-RCD may have anomalies in systems supporting language and memory processes. Those anomalies may, in turn, contribute to weaknesses in semantic memory and, consequently, reading comprehension.

Ryherd and colleagues (2018) took a different approach to a similar concept, using functional neuroimaging to investigate the functional neural activation to spoken and printed single words and passages in adolescents with a range of reading comprehension abilities. They found that adolescents' reading comprehension abilities were negatively related to functional neural activation in regions associated with executive function and memory, such as the anterior cingulate cortex, insula, and hippocampus. This finding, which supports the finding of Cutting and colleagues (2013), implies that retrieval and, thus, comprehension are more effortful for poor comprehenders, such as those with S-RCD, than good comprehenders. The consistency of these results across spoken and written word modalities supports the idea that S-RCD involves, in part, a language comprehension deficit that also manifests in difficulty with comprehending written text (Ryherd et al., 2018). More research, especially using stimuli that involve lengthier passages, is needed to fully understand the origins of distinct brain patterns observed in individuals with S-RCD.

Neurobiology of Reading: Current and Future Directions

The aforementioned findings briefly reviewed in this chapter offer a window into word recognition and reading comprehension processes in terms of understanding the neurobiological correlates of learning disorders in these areas. Nonetheless, it is notable that most neurobiological models relevant to reading development and disorders have not broken down brain regions linked to word-, sentence-, and discourse-level processes. Admittedly, this is a highly complex task, made even more complex when trying to apply any summarized literature to understanding learning disorders because there are far more studies of word-level versus comprehension-level processes in developing readers/reading impairment. However, it is of value to consider a model that does include word-, sentence-, and comprehension-level processes, especially including more recent studies, which have sought to examine how executive brain regions are involved in the reading process in developing readers. To that end, here in Figure 5.1 (pp. 110–111), we include a model of reading (left hemisphere only) that attempts to incorporate not only those areas commonly noted in word recognition models (e.g., Kearns et al., 2019), but also extends to incorporate comprehension-level processes, as well as begin to think about how executive function regions may be involved in reading. Of note, this model should be viewed as *exploratory* and *underdeveloped*, as it is based largely on meta-analyses with adults along with some specific studies in adolescents; nonetheless, it provides a beginning point for thinking about reading processes that span from word to comprehension-levels and, thus, in turn, begins to set the stage for a reference point for considering neurobiological processes involved with reading development and reading difficulties that include not only word-level but also comprehension-level processes. A fully developed model will need to consider what cognitive processes each core region is engaging in (e.g., lexical processing, phonological processing, semantic integration, etc.) and which regions are anomalous in poor readers, as well as consider how these key regions map onto known brain networks (e.g., fronto–parietal network, default mode network, etc.) (cf., Bailey et al., 2018).

Math

It has been estimated that between 5% and 8% of all students have a math disability (Badian & Ghublikian, 1983; Gross-Tsur et al., 1996; Ostad, 1997; Shalev et al., 2000), with 2.5 million students receiving special education services in United States public schools for math disabilities (Cortiella & Horowitz, 2014). These figures make math disabilities the second-most common learning disability after reading disabilities. However, the literature investigating math disabilities is not nearly as expansive nor as robust in comparison to the literature investigating reading disabilities (Mazzocco, 2005). Math cognition and math disabilities are currently very understudied.

Similar to reading and reading disabilities, the effects of poor math skills on personal and public health make the importance of understanding math development and math disabilities strikingly apparent. Poor math skills have been associated with academic underachievement (Duncan et al., 2007), school dropout (Bynner & Parsons, 1997, 2000), underemployment (Bynner & Parsons, 1997, 2000; Ritchie & Bates, 2013), mental and/or physical illness (Parsons & Bynner, 2005), and/or incarceration (Parsons & Bynner, 2005). Math skills are especially important now more than ever because knowledge of numbers is increasingly required in our increasingly technological, "data-drenched" society (MacKinnon McQuarrie et al., 2014; Steen, 1999). Similar to reading disabilities, all of these aforementioned adverse outcomes cost taxpayer dollars, thus making math disabilities a public health concern; it has even been estimated that math disabilities cost society more money than reading disabilities (Gross et al., 2009; Sheuermann & Pedró, 2010).

Earlier identification of students with math disabilities and earlier intervention for such disabilities would help lessen the need for these resources and therefore lower their costs. Indeed, it is important to study math and, moreover, math disabilities in hopes of eventually remediating these disabilities, ultimately alleviating these adverse consequences. In the following section, we briefly review literature on the cognition and neurobiological correlates of math and math disabilities.

Math Cognition

Math is conceptualized as a domain-specific area of knowledge with distinct cortical correlates (Amalric & Dehaene, 2019). Studies conducted with typically developing/developed populations have established that math relies on both domain-general skills, including spatial skills, visuospatial working memory, and cognitive control, in addition to domain-specific skills, including number sense, quantity manipulation, arithmetic fact retrieval, and problem solving (Menon & Chang, 2021; Soares et al., 2018; Tam et al., 2019). Math can be studied using symbolic stimuli (Arabic numbers), nonsymbolic stimuli (dots), and auditory and visual number words. It is thought that the cognitive mechanisms underlying math, which are both domain-general and domain-specific (to math), account for the link between the processing of nonsymbolic and symbolic magnitudes and their relations to math (Price & Wilkey, 2017).

A foundational concept underlying math is numeracy, or "the universal ability to represent and manipulate numerical magnitudes nonverbally on a spatially oriented mental number line" (von Aster & Shalev, 2007). Put simply, numeracy is one's familiarity and comfort with quantities and numbers. Numeracy extends beyond basic arithmetic, involving the application of math beyond the classroom and in the real world. Somewhat encompassed in numeracy but somewhat unique, two other foundational concepts of math are ordinality and cardinality. Ordinality refers to the ability to place numbers in a sequence (Lyons et al., 2016). Cardinality is the quantity represented by the number symbol (Geary et al., 2018).

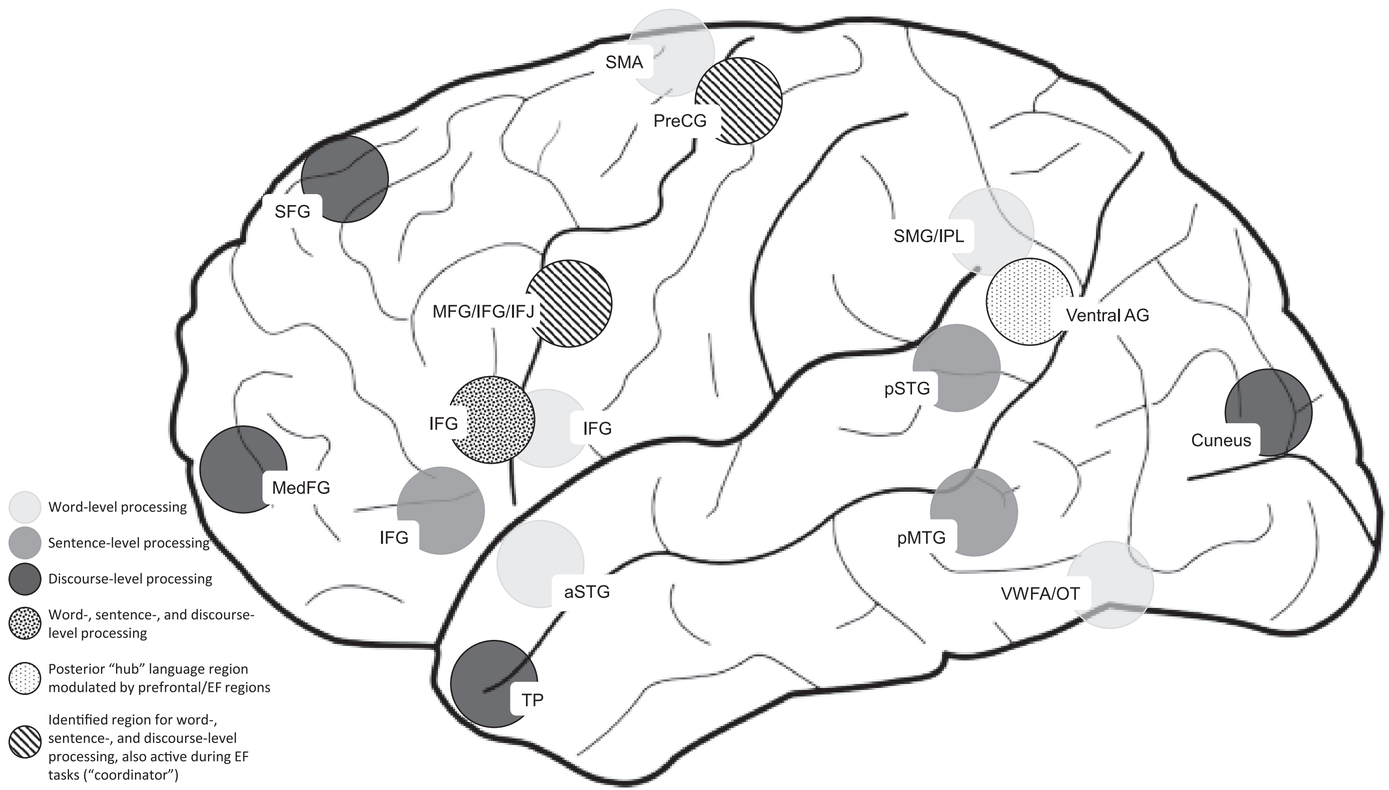
SMA
PreCG
SFG
MFG/IFG/IFJ
IFG
IFG
MedFG
IFG
aSTG
TP
SMG/IPL
Ventral AG
pSTG
Cuneus
pMTG
VWFA/OT
Word-level processing
Sentence-level processing
Discourse-level processing
Word-, sentence-, and discourse-level processing
Posterior "hub" language region modulated by prefrontal/EF regions
Identified region for word-, sentence-, and discourse-level processing, also active during EF tasks ("coordinator")

FIGURE 5.1. Visual depiction of the proposed neurobiological model of reading and executive function. SFG = superior frontal gyrus; MedFG = medial frontal gyrus; MFG = middle frontal gyrus; IFG = inferior frontal gyrus; IFJ = inferior frontal junction; SMA = supplementary motor area; PreCG = precentral gyrus; SMG/IPL = supramarginal gyrus/inferior parietal lobule; AG = angular gyrus; pSTG = posterior superior temporal gyrus; pMTG = posterior middle temporal gyrus; VWFA/OT = visual word form area/occipital-temporal region; aSTG = anterior superior temporal gyrus; TP = temporal pole. Note that the cuneus and MedFG are medial, but for visualization purposes have been placed in more lateral positions.

Note. The proposed neurobiological model of reading and executive function is a synthesis of an activation map derived from Neurosynth (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011), meta-analyses (Martin, Schurz, Kronbichler, & Richlan, 2015; Walenski, Europa, Caplan, & Thompson, 2019; Yang et al., 2019), individual fMRI studies that have tried to understand how executive function may be related to reading processes (Aboud, Bailey, Petrill, & Cutting, 2016; Kim et al., 2022; Wang et al., 2020) and review papers (Banich et al., 2023; Church, Cirino, Miciak, Juranek, Vaughn, & Fletcher, 2019; Kearns, Hancock, Hoeft, Pugh, & Frost, 2019). Using Neurosynth (neurosynth.org), which is a database of fMRI studies across broad topic areas, we searched "reading" using the "term search" function to obtain a synthesized brain activation map from 521 studies of reading and the brain to broadly capture the brain regions proposed to be involved in reading. While this activation map provided a starting point, the 521 studies that comprise it were too diverse (different ages, diagnoses, different levels of reading, etc.) resulting in many brain regions. To narrow down the brain regions involved in word-, sentence- and comprehension-level processes, we used existing meta-analyses for word- (Martin et al., 2015), sentence- (Walenski et al., 2019) and discourse-level processing (Yang et al., 2019). Finally, we identified executive brain regions involved in reading using individual fMRI studies (Aboud et al., 2016; Wang et al., 2020; Kim et al., 2022). For each left lateralized peak coordinate identified in each of the aforementioned meta-analyses and individual studies, we created a region of interest (5mm or 10mm spheres). We then analyzed the overlaps of neurosynth and the masks from each paper for each brain region. From these overlaps, we propose the process(es) that each brain region supports during reading tasks. The proposed ventral AG posterior "hub" language region modulated by prefrontal/EF is largely derived from the results of Kim et al. (2022).

People are thought to mentally represent numbers along a horizontal, imaginary number line, situated from left to right (Galton, 1880). Called the "mental number line representation," this concept is supported by a diverse group of studies, including those of clinical populations with spatial neglect (Vuilleumier et al., 2004), those involving response time (Dehaene et al., 1993), and those involving number comparisons (Moyer & Landauer, 1967). Given the spatial characteristics and setup of the mental number line representation, the mental number line supports the theory that spatial skills underlie math skills (Tam et al., 2019).

Math Disabilities

Math disability is a specific learning disability characterized by difficulties in processing numerical and mathematical information despite at least average intelligence and at least adequate math instruction (Berch & Mazzocco, 2007; Butterworth et al., 2011; Kaufmann et al., 2013; Price & Ansari, 2013). The DSM-5 defines math disability as a "specific learning disorder" "with impairment in mathematics," with noted impairment(s) in number sense, memorization of arithmetic facts, accurate and/or fluent calculation, and/or accurate math reasoning (American Psychiatric Association, 2013). Math disabilities are sometimes referred to as "developmental dyscalculia" (Price & Ansari, 2013).

Researchers have proposed several different models of typical and atypical math learning in attempts to explain the cognitive components of math and math disabilities. These models have not been published long enough for the field to fully test and empirically conclude which singular model or combination of models is likely the most accurate. That being said, the arguably most influential model is currently the triple code model (Skagenholt et al., 2018). The triple code model posits that there are three independent domains of math: (1) numerical quantity representation, (2) visuospatial numerical representation, and (3) auditory verbal representation (Dehaene & Cohen, 1995; Wilson & Dehaene, 2007). This model was based on findings from samples of educated adults, so it has yet to be studied through a developmental or disordered perspective; for this reason and other reasons, further model testing is necessary (Siemann & Petermann, 2018). However, early neuroimaging evidence linking these three domains to three distinct brain regions (intraparietal sulcus, posterior superior parietal lobule, and angular gyrus) provides support for this model (Soares et al., 2018).

While the triple code model is currently arguably the most influential model of math cognition (Skagenholt et al., 2018), there are several other models of typical and atypical math cognition. The "core deficit hypothesis," which can broadly be applied to several disorders, including math disabilities, posits that math disabilities stem from one foundational deficit (Astle & Fletcher-Watson, 2020; Soares et al., 2018). That foundational deficit could be perception and processing of number magnitude (Landerl et al., 2004), general numeracy (Robinson et al., 2002), or something else, but ultimately, it is one foundational deficit that causes all other mathematical difficulties. Another model suggests that math disabilities derive from deficits in domain-general skills that underlie the impaired math skills. In this model, deficits in basic skills, such as verbal working memory, long-term memory, and visuospatial processing, are thought to cause math disabilities (Geary, 2004). Working memory, in particular, plays an integral role in mathematical learning; visuospatial working memory deficits also contribute to dyscalculia (Menon, 2016). Another model, the "procedural deficit hypothesis" of math disability, suggests that abnormalities of brain structures underlying the procedural memory system can lead to difficulties with math skills and other functions associated with these structures (Ullman, 2004). Clinicians have also posited their own models. One of the main clinical models decomposes math disabilities into four main skills/deficits: core number skills, memory, reasoning, and visuospatial skills (Karagiannakis et al., 2014).

Again, all of these models must be viewed with caution as they do not yet have substantial empirical support. For example, emerging evidence indicates that the deficits in numerical magnitude processing and perception previously posited to cause math disabilities may actually be more reflective of deficits in executive function, specifically inhibitory control demands from incongruent visual cues in a nonsymbolic number comparison task (Wilkey et al., 2020). Additionally, a significant portion of math disabilities cannot be explained by the procedural deficit model (Soares et al., 2018). More research into typical and atypical math learning, to ultimately achieve consensus on a theoretical model of math cognition (like the SVR in reading), is needed.

Neurobiological Correlates of Math and Math Disabilities

Canonical research investigating the neurobiological correlates of math indicates that both hemispheres of the brain are involved. However, emerging evidence suggests that during math cognition, the right hemisphere might be more involved than the left (Ashkenazi et al., 2013). Three key brain regions involved in math cognition include: (1) the bilateral intraparietal cortices, (2) the bilateral prefrontal cortices (Dastjerdi et al., 2013; Eger, 2016), and (3) the bilateral inferior temporal cortices (Daitch et al., 2016; Park et al., 2014; Shum et al., 2013). The bilateral intraparietal cortex is involved in the processing of symbolic numerical information and visuospatial working memory (Matejko & Ansari, 2017). The bilateral prefrontal cortex has been linked to cognitive control, attention, inhibition, prospective memory, and cognitive flexibility (Armbruster et al., 2012). The inferior temporal cortex is associated with visual processing and object recognition (Bar et al., 2001; Miyashita, 1993). Recent research suggests that similar to the robust VWFA seen in tasks related to language and reading, math might have its own devoted region. Termed the "number form area" (NFA), this region is located in the right posterior inferior temporal gyrus of the inferior temporal cortex (Abboud et al., 2015; Daitch et al., 2016; Yeo et al., 2017).

The bilateral intraparietal sulci (IPS), located in the bilateral intraparietal cortices, in particular, appear to be the most important brain regions involved in math cognition (Amalric & Dehaene, 2019; Cohen Kadosh et al., 2008; Dehaene et al., 2003; Monti et al., 2012; Pinel et al., 2001; Price et al., 2007). The IPS is thought to support the processing of numerical magnitude (Ansari & Dhital, 2006; Cantlon & Brannon, 2006; Cantlon et al., 2006). However, other brain regions beyond the IPS are also involved in math cognition. There is increasing support for the involvement of the left angular gyrus in math tasks, particularly those involving the processing of numerical symbols (Price & Ansari, 2011) and arithmetic facts (Butterworth et al., 2011; Delazer et al., 2005). The right inferior frontal gyrus is broadly associated with numeracy and, more specifically, with attention to numbers, rendering it important for math cognition (Wilkey & Price, 2019). Other brain regions involved in math-related tasks include (but are not limited to) the bilateral hippocampus, parahippocampal gyrus, perisylvian areas, and fusiform gyrus (Butterworth et al., 2011; Cho et al., 2012; Menon & Chang, 2021; Soares et al., 2018; Wilkey et al., 2017).

The lack of consensus surrounding the brain regions involved in math cognition seems to result from several factors. One such factor is the overall paucity of math studies that use neuroimaging. Another factor is the diversity in the functional neuroimaging tasks used to study brain activation during math-related tasks (examples of tasks include symbolic vs. nonsymbolic tasks, tasks involving magnitude comparisons, tasks involving arithmetic, tasks involving more or less language/reading, etc.) hindering consensus. An additional factor is the widespread use of region-of-interest (ROI) analyses, which involve a priori selection of one specific brain region for intense study. The bilateral intraparietal sulci are understandably commonly used as ROIs in math studies. However, whole-brain analyses that could potentially identify more brain regions involved in math are consequently lacking. More and perhaps more cooperative studies need to be conducted to reach consensus surrounding the brain regions involved in math cognition.

Math Disabilities

The few math-related neuroimaging studies that have been published have generally concluded that individuals with math disabilities exhibit functional differences in both brain hemispheres (Soares et al., 2018), especially the right hemisphere (Ashkenazi et al., 2013), as compared to individuals without math disabilities. These functional differences generally include both underactivation and overactivation in various brain regions (Ashkenazi et al., 2013; Soares et al., 2018). Individuals with math disabilities also tend to exhibit structural brain differences, but those differences will not be discussed in this chapter.

Studies have shown that children with math disabilities have anomalous activation patterns in the bilateral intraparietal sulci compared to their typically developing peers (Mussolin et al., 2010; Price et al., 2007). Some studies demonstrate that children with math disabilities exhibit overactivation of the intraparietal sulci (Kaufmann et al., 2009). Kaufmann and colleagues suggest that overactivation of the intraparietal sulci somehow compensates for the deficits in math subskills (Kaufmann et al., 2009). However, other studies demonstrate that children with math disabilities actually show underactivation in the intraparietal sulci as compared to typically developing children in numeric magnitude differentiation tasks (Mussolin et al., 2010) and performing arithmetic (Kucian et al., 2006). While

Mussolin and colleagues (2010) had initially predicted overactivation in the intraparietal sulci, due to the extra effort exerted by children with math disabilities while completing math tasks as compared to typically developing peers, they actually observed decreased activation in those regions (Mussolin et al., 2010). Mussolin and colleagues therefore broadly conclude that the "lack of IPS sensitivity" in children with math disabilities as compared to typically developing children "concerns domain-specific and domain-general magnitudes" (Mussolin et al., 2010). Similarly, Kucian and colleagues conclude that the weaker activation they observed in the intraparietal sulci in children with math disabilities as compared to typically developing peers was due to a broad lack of recruitment across relevant brain regions (Kucian et al., 2006).

While the findings regarding intraparietal sulci activation are the most commonly reported in those with math disabilities, other brain regions have also been reported to show anomalous activation in children with math disabilities as compared to those without. While findings are relatively inconsistent, children with math disabilities typically exhibit decreased activation in several regions outside the math network (the math network being the intraparietal sulci, angular gyrus, and posterior superior parietal lobule), such as the right middle frontal gyrus and premotor cortex within the prefrontal cortex, the right insula, the right parahippocampal gyrus, and the left cingulate gyrus (Ashkenazi et al., 2012; Kucian et al., 2006; Mussolin et al., 2010) as compared to typically developing peers. Additionally, children with math disabilities exhibit overactivations in the right postcentral gyrus and the right supramarginal gyrus as compared to typically developing peers. Overactivation of the right postcentral gyrus is thought to relate to the increased sensorimotor demands on children with math disabilities when doing math (Mussolin et al., 2010; Pinel et al., 1999). While there are several potential explanations, overactivation of the right supramarginal gyrus is thought to relate to the increased visuospatial working memory required for children with math disabilities to do math (Mussolin et al., 2010). More research is needed to fully understand the origins of distinct brain patterns observed in individuals with math disabilities.

Comorbidity of Reading and Math

Reading and math disabilities are typically studied separately, but they are highly comorbid. A "comorbidity" occurs when another condition or conditions accompanies the primary condition of study (Feinstein, 1970). Reading and math disabilities commonly co-occur and are actually more likely to co-occur than present in isolation (Joyner & Wagner, 2020). Estimates vary based on diagnostic criteria, but approximately 56% of students with reading disabilities also have math disabilities, and approximately 70% of students with math disabilities also have reading disabilities (Barbaresi et al., 2005; Dirks et al., 2008). Indeed, a meta-analysis by Joyner and Wagner (2020) found that there are varying degrees of comorbidity between reading and math disabilities (e.g., Badian, 1999; Barbaresi et al., 2005; Branum-Martin et al., 2013; Dirks et al., 2008; Lewis et al., 1994; Light & DeFries, 1995).

The underlying cognitive skills required for reading and math may provide insight into this comorbidity. Both reading and math are linked to phonological processing (De Smedt & Boets, 2010; Hecht et al., 2001), memory (Hecht et al., 2001; Swanson & Jerman, 2006; Swanson et al., 2009), and executive function (Yeniad et al., 2013). Additionally, there are similarities between letters in alphabetic writing and digits in math (Joyner & Wagner, 2020). Finally, especially as one first learns math through stories and word problems, much of the instruction and computation of math requires language and reading (Joyner & Wagner, 2020). It has actually been suggested that reading disability be included as a diagnostic criterion of math disability (Joyner & Wagner, 2020). Unsurprisingly, comorbidities across both reading and math disabilities include deficits in executive function (Lonergan et al., 2019; Morgan et al., 2017; Yeniad et al., 2013), ADHD (Mayes & Calhoun, 2006; Willcutt & Pennington, 2000), and mental health conditions including anxiety and/or depression (Krinzinger et al., 2009; Mammarella et al., 2016). Discussion of comorbidity is beyond the scope of this chapter (see Willcutt, this volume, for an in-depth review of comorbidity across learning disabilities and psychiatric disorders). However, many of the cognitive studies and most of the neurobiological studies, to date, have not considered the effects of comorbidities. This raises an important caveat of the majority of the neurobiological findings to date; whether the neuroimaging findings reviewed in this chapter vary based on comorbidity status is currently an unanswered question.

Conclusions

Reading and math disabilities are thought to be the most common learning disabilities. Reading has been studied rather extensively, but research in math disabilities lags in comparison. More basic and translational research must be done to understand the core deficits of these types of disabilities, and especially whether comorbid reading and math disabilities have different developmental sequalae and neurobiological origins. Indeed, a better understanding of these disabilities is essential for the improvement of diagnostic criteria and interventions. If individuals with these disabilities can be diagnosed earlier, tailored interventions can be implemented earlier and thus result in better outcomes. Greater specificity and clarity can also refine the nebulous systems of names and diagnostic criteria that muddy the research and clinical practice of these disabilities, which will ultimately help researchers, practitioners, educators, parents, and individuals with the disabilities themselves.

AUTHORS' NOTE

The studies cited throughout this book chapter are quite heterogeneous in their samples, diagnostic criteria, and neuroimaging equipment used (if applicable). Samples of participants include wide age ranges, different age ranges, various comorbidities, and different

English language capabilities. Diagnostic criteria vary widely in percentile (5th to 35th percentile), in criteria (one-third assessments below a certain percentile, all of the assessments below a certain percentile), and in assessment (Woodcock–Johnson, CTOPP, etc.). Neuroimaging studies use different types of equipment and techniques (EEG, structural and functional MRI, PET, etc.); scanners can be a confound when comparing studies. It is therefore of the utmost importance to synthesize information and generalize findings across studies with caution.

REFERENCES

Aaron, P. G., Joshi, R. M., Boulware-Gooden, R., & Bentum, K. (2008). Diagnosis and treatment of reading disabilities based on the component model of reading: An alternative to the discrepancy model of learning disabilities. *Journal of Learning Disabilities, 4*(1), 67–84.

Aboud, K. S., Bailey, S. K., Del Tufo, S. N., Barquero, L. A., & Cutting, L. E. (2019). Fairy tales versus facts: Genre matters to the developing brain. *Cerebral Cortex, 29*(11), 4877–4888.

Aboud, K. S., Bailey, S. K., Petrill, S. A., & Cutting, L. E. (2016). Comprehending text versus reading words in young readers with varying reading ability: Distinct patterns of functional connectivity from common processing hubs. *Developmental Science, 19*(4), 632–656.

Abboud, S., Maidenbaum, S., Dehaene, S., & Amedi, A. (2015). A number-form area in the blind. *Nature Communications, 6*, 6026.

Amalric, M., & Dehaene, S. (2019). A distinct cortical network for mathematical knowledge in the human brain. *NeuroImage, 189*, 19–31.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Author.

Ansari, D., & Dhital, B. (2006). Age-related changes in the activation of the intraparietal sulcus during nonsymbolic magnitude processing: An event-related functional magnetic resonance imaging study. *Journal of Cognitive Neuroscience, 18*(11), 1820–1828.

Armbruster, D. J., Ueltzhöffer, K., Basten, U., & Fiebach, C. J. (2012). Prefrontal cortical mechanisms underlying individual differences in cognitive flexibility and stability. *Journal of Cognitive Neuroscience, 24*(12), 2385–2399.

Ashkenazi, S., Black, J. M., Abrams, D. A., Hoeft, F., & Menon, V. (2013). Neurobiological underpinnings of math and reading learning disabilities. *Journal of Learning Disabilities, 46*(6), 549–569.

Ashkenazi, S., Rosenberg-Lee, M., Tenison, C., & Menon, V. (2012). Weak task-related modulation and stimulus representations during arithmetic problem solving in children with developmental dyscalculia. *Developmental Cognitive Neuroscience, 2*(Suppl. 1), S152–S166.

Astle, D. E., & Fletcher-Watson, S. (2020). Beyond the core-deficit hypothesis in developmental disorders. *Current Directions in Psychological Science, 29*(5), 431–437.

Badian, N. A. (1999). Persistent arithmetic, reading, or arithmetic and reading disability. *Annals of Dyslexia, 49*, 45–70.

Badian, N. A., & Ghublikian, M. (1983). The personal-social characteristics of children with poor mathematical computation skills. *Journal of Learning Disabilities, 16*(3), 154–157.

Bailey, S. K., Aboud, K. S., Nguyen, T. Q., & Cutting, L. E. (2018). Applying a network framework to the neurobiology of reading and dyslexia. *Journal of Neurodevelopmental Disorders, 10*, 37.

Banich, M. T., Wang, K., Kim, H., Leopold, D. R., Reineberg, A. E., Thompson, L. A., et al. (2023). The influence of executive processing on reading comprehension during adolescence. *Mind, Brain, and Education, 17*(4), 279–288.

Bar, M., Tootell, R. B., Schacter, D. L., Greve, D. N., Fischl, B., Mendola, J. D., et al. (2001). Cortical mechanisms specific to explicit visual object recognition. *Neuron, 29*(2), 529–535.

Barbaresi, W. J., Katusic, S. K., Colligan, R. C., Weaver, A. L., & Jacobsen, S. J. (2005). Math learning disorder: Incidence in a population-based birth cohort, 1976–82, *Ambulatory Pediatrics: The Official Journal of the Ambulatory Pediatric Association, 5*(5), 281–289.

Ben-Shachar, M., Dougherty, R. F., Deutsch, G. K., & Wandell, B. A. (2011). The development of cortical sensitivity to visual word forms. *Journal of Cognitive Neuroscience, 23*(9), 2387–2399.

Berch, D. B., & Mazzocco, M. M. M. (Eds.). (2007). *Why is math so hard for some children? The nature and origins of mathematical learning difficulties and disabilities*. Brookes.

Black, J. M., Xia, Z., & Hoeft, F. (2017). Neurobiological bases of reading disorder part II: The importance of developmental considerations in typical and atypical reading. *Language and Linguistics Compass, 11*(10), e12252.

Branum-Martin, L., Fletcher, J. M., & Stuebing, K. K. (2013). Classification and identification of reading and math disabilities: The special case of comorbidity. *Journal of Learning Disabilities, 46*(6), 490–499.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From brain to education. *Science, 332*(6033), 1049–1053.

Bynner, J., & Parsons, S. (1997). *Does numeracy matter? Evidence from the National Child Development Study on the impact of poor numeracy on adult life*. Basic Skills Agency.

Bynner, J., & Parsons, S. (2000). Impact of poor numeracy on employment and career progression. In C. Tikly & A. Wolf (Eds.), *The maths we need now: Demands, deficits and remedies*. (pp. 26–51). Bedford Way Papers.

Cain, K., & Oakhill, J. V. (1999). Inference making ability and its relation to comprehension failure in young children. *Reading and Writing, 11*, 489–503.

Cain, K., & Oakhill, J. V. (2006). Profiles of children with specific reading comprehension difficulties. *British Journal of Educational Psychology, 76*(4), 683–696.

Cain, K., Oakhill, J. V., & Bryant, P. (2004). Children's reading comprehension ability: Concurrent prediction by working memory, verbal ability, and component skills. *Journal of Educational Psychology, 96*(1), 31–42.

Cantlon, J. F., & Brannon, E. M. (2006). Shared system for ordering small and large numbers in monkeys and humans. *Psychological Science, 17*(5), 401–406.

Cantlon, J. F., Brannon, E. M., Carter, E. J., & Pelphrey, K. A. (2006). Functional imaging of numerical processing in adults and 4-y-old children. *PLOS Biology, 4*(5), e125.

Carroll, J. M., Maughan, B., Goodman, R., & Meltzer, H. (2005). Literacy difficulties and psychiatric disorders: Evidence for comorbidity. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 46*(5), 524–532.

Carver, R. P. (1997). Reading for one second, one minute, or one year from the perspective of Rauding theory. *Scientific Studies of Reading, 1*(1), 3–43.

Carver, R. P. (2003). The highly lawful relationships among pseudoword decoding, word identification, spelling, listening, and reading. *Scientific Studies of Reading, 7*(2), 127–154.

Catts, H. W., Adlof, S. M., & Ellis Weismer, S. (2006). Language deficits in poor comprehenders: A case for the simple view of reading. *Journal of Speech, Language, and Hearing Research: JSLHR, 49*(2), 278–293.

Catts, H. W., Hogan, T. P., & Fey, M. E. (2003). Subgrouping poor readers on the basis of individual differences in reading-related abilities. *Journal of Learning Disabilities, 36*(2), 151–164.

Center on Budget and Policy Priorities. (2022). *Where do our federal tax dollars go? www.cbpp.org/research/federal-budget/where-do-our-federal-tax-dollars-go*.

Cho, S., Metcalfe, A. W., Young, C. B., Ryali, S., Geary, D. C., & Menon, V. (2012). Hippocampal–prefrontal engagement and dynamic causal interactions in the maturation of children's fact retrieval. *Journal of Cognitive Neuroscience, 24*(9), 1849–1866.

Christle, C. A., & Yell, M. L. (2008). Preventing youth incarceration through reading remediation: Issues and solutions. *Reading & Writing Quarterly, 24*(2), 148–176.

Church, J. A., Cirino, P. T., Miciak, J., Juranek, J., Vaughn, S., & Fletcher, J. M. (2019). Cognitive, intervention, and neuroimaging perspectives on executive function in children with reading disabilities. *New Directions for Child and Adolescent Development, 2019*(165), 25–54.

Clarke, P. J., Snowling, M. J., Truelove, E., & Hulme, C. (2010). Ameliorating children's reading-comprehension difficulties: A randomized controlled trial. *Psychological Science, 21*(8), 1106–1116.

Cohen, L., Lehéricy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain: A Journal of Neurology, 125*(Pt. 5), 1054–1069.

Cohen Kadosh, R., Lammertyn, J., & Izard, V. (2008). Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. *Progress in Neurobiology, 84*(2), 132–147.

Cortiella, C., & Horowitz, S. H. (2014). *The state of learning disabilities: Facts, trends and emerging issues* (3rd ed.). National Center for Learning Disabilities.

Cromley, J. G., & Azevedo, R. (2007). Testing and refining the direct and inferential mediation model of reading comprehension. *Journal of Educational Psychology, 99*(2), 311–325.

Curtis, M. E. (1980). Development of components of reading skill. *Journal of Educational Psychology, 72*(5), 656–669.

Cutting, L. E., Clements-Stephens, A., Pugh, K. R., Burns, S., Cao, A., Pekar, J. J., et al. (2013). Not all reading disabilities are dyslexia: Distinct neurobiology of specific comprehension deficits. *Brain Connectivity, 3*(2), 199–211.

Cutting, L. E., & Scarborough, H. S. (2006). Prediction of reading comprehension: Relative contributions of word recognition, language proficiency, and other cognitive skills can depend on how comprehension is measured. *Scientific Studies of Reading, 10*(3), 277–299.

D'Mello, A. M., & Gabrieli, J. D. E. (2018). Cognitive neuroscience of dyslexia. *Language, Speech, and Hearing Services in Schools, 49*(4), 798–809.

Daitch, A. L., Foster, B. L., Schrouff, J., Rangarajan, V., Kaşikçi, I., Gattas, S., et al. (2016). Mapping human temporal and parietal neuronal population activity and functional coupling during mathematical cognition. *Proceedings of the National Academy of Sciences of the United States of America, 113*(46), E7277–E7286.

Daniel, S. S., Walsh, A. K., Goldston, D. B., Arnold, E. M., Reboussin, B. A., & Wood, F. B. (2006). Suicidality, school dropout, and reading problems among adolescents. *Journal of Learning Disabilities, 39*(6), 507–514.

Dastjerdi, M., Ozker, M., Foster, B., Rangarajan, V., & Parvizi, J. (2013). Numerical processing in the human parietal cortex during experimental and natural conditions. *Nature Communications, 4*, 25–28.

De Smedt, B., & Boets, B. (2010). Phonological processing and arithmetic fact retrieval: Evidence from developmental dyslexia. *Neuropsychologia, 48*(14), 3973–3981.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*(3), 371–396.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*(1), 83–120.

Dehaene, S., Pegado, F., Braga, L. W., Ventura, P., Nunes Filho, G., Jobert, A., et al. (2010). How learning to read changes the cortical networks for vision and language. *Science, 330*(6009), 1359–1364.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3–6), 487–506.

Delazer, M., Ischebeck, A., Domahs, F., Zamarian, L., Koppelstaetter, F., Siedentopf, C. M., et al. (2005). Learning by strategies and learning by drill—evidence from an fMRI study. *NeuroImage, 25*(3), 838–849.

Dirks, E., Spyer, G., Van Lieshout, E. C. D. M., & De Sonneville, L. (2008). Prevalence of combined reading and arithmetic disabilities. *Journal of Learning Disabilities, 41*(5), 460–473.

Duke, N. K., & Cartwright, K. B. (2021). The science of reading progresses: Communicating advances beyond the Simple View of Reading. *Reading Research Quarterly, 56*(51), S25–S44.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., et al. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446.

Eger, E. (2016). Neuronal foundations of human numerical representations. *Progress in Brain Research, 227*, 1–27.

Ehrlich, M. F., Remond, M., & Tardieu, H. (1999). Processing of anaphoric devices in young skilled and less skilled comprehenders: Differences in metacognitive monitoring. *Reading and Writing, 11*, 29–63.

Feinstein, A. R. (1970). The pre-therapeutic classification of co-morbidity in chronic disease. *Journal of Chronic Diseases, 23*(7), 455–468.

Fiez, J. A., & Petersen, S. E. (1998). Neuroimaging studies of word reading. *Proceedings of the National Academy of Sciences of the United States of America, 95*(3), 914–921.

Fletcher, J. M., Lyon, G. R., Fuchs, L. S., & Barnes, M. A. (2007). *Learning disabilities: From identification to intervention*. Guilford Press.

Foorman, B. R., Francis, D. J., Shaywitz, S. E., Shaywitz, B. A., & Fletcher, J. M. (1997). The case for early reading intervention. In B. A. Blachman (Ed.), *Foundations of reading acquisition and dyslexia: Implications for early intervention* (pp. 243–264). Erlbaum.

Francis, D. J., Fletcher, J. M., Catts, H. W., & Tomblin, J. B. (2005). Dimensions affecting the assessment of reading comprehension. In S. G. Paris & S. A. Stahl (Eds.), *Children's reading comprehension and assessment* (pp. 369–394). Erlbaum.

Fuchs, D., Fuchs, L. S., & Vaughn, S. (2014). What is intensive instruction and why is it important? *Teaching Exceptional Children, 46*(4), 13–18.

Gabrieli, J. D. (2009). Dyslexia: A new synergy between education and cognitive neuroscience. *Science, 325*(5938), 280–283.

Galton, F. (1880). Visualised numerals. *Nature, 21*, 252–256.

Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37*(1), 4–15.

Geary, D. C., VanMarle, K., Chu, F. W., Rouder, J., Hoard, M. K., & Nugent, L. (2018). Early conceptual understanding of cardinality predicts superior school-entry number-system knowledge. *Psychological Science, 29*(2), 191–205.

Gernsbacher, M. A., & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 17*(2), 245–262.

Goff, D. A., Pratt, C., & Ong, B. (2005). The relations between children's reading comprehension, working memory, language skills and components of reading decoding in a normal sample. *Reading and Writing: An Interdisciplinary Journal, 18*(7–9), 583–616.

Gough, P. B., & Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial and Special Education, 7*(1), 6–10.

Grigorenko, E. L. (2001). Developmental dyslexia: An update on genes, brains, and environments. *Journal of Child Psychology and Psychiatry, 42*(1), 91–125.

Gross, J., Hudson, C., & Price, D. (2009). *The long term costs of numeracy difficulties*. National Numeracy. *www.nationalnumeracy.org.uk/research-and-resources/long-term-costs-numeracy-difficulties-2008*

Gross-Tsur, V., Manor, O., & Shalev, R. S. (1996). Developmental dyscalculia: Prevalence and demographic features. *Developmental Medicine and Child Neurology, 38*(1), 25–33.

Harrison, A. G., & Stewart, M. (2019). Diagnostic implications of the double deficit model for young adolescents with dyslexia. *Dyslexia, 25*(4), 345–359.

Hecht, S. A., Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2001). The relations between phonological processing abilities and emerging individual differences in mathematical computation skills: A longitudinal study from second to fifth grades. *Journal of Experimental Child Psychology, 79*(2), 192–227.

Henderson, L., Snowling, M., & Clarke, P. (2013). Accessing, integrating, and inhibiting word meaning in poor comprehenders. *Scientific Studies of Reading, 17*(3), 177–198.

Hoeft, F., Ueno, T., Reiss, A. L., Meyler, A., Whitfield-Gabrieli, S., Glover, G. H., et al. (2007). Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. *Behavioral Neuroscience, 121*(3), 602–613.

Hoover, W. A., & Gough, P. B. (1990). The Simple View of Reading. *Reading and Writing, 2*(2), 127–160.

Hoover, W. A., & Tunmer, W. E. (2020). *The cognitive foundations of reading and its acquisition*. Springer.

Horowitz, S. H., Rawe, J., & Whittaker, M. C. (2017). *The state of learning disabilities: Understanding the 1 in 5*. National Center for Learning Disabilities.

Horowitz-Kraus, T., Wang, Y., Plante, E., & Holland, S. K. (2014). Involvement of the right hemisphere in reading comprehension: A DTI study. *Brain Research, 1582*, 34–44.

Hudson, N., Scheff, J., Tarsha, M., & Cutting, L. E. (2016). Reading comprehension and executive function neurobiological findings. *Perspectives on Language and Literacy, 42*(2), 23–29.

Hulme, C., & Snowling, M. (2011). Children's reading comprehension difficulties: Nature, causes, and treatments. *Current Directions in Psychological Science, 20*(3), 139–142.

Individuals with Disabilities Education Act, 20 U.S.C. § 1400 (2004).

Johns, C. L., Tooley, K. M., & Traxler, M. J. (2008). Discourse impairments following right hemisphere brain damage: A critical review. *Language and Linguistics Compass, 2*(6), 1038–1062.

Joseph, J., Noble, K., & Eden, G. (2001). The neurobiological basis of reading. *Journal of Learning Disabilities, 34*(6), 566–579.

Joshi, R. M., Williams, K., & Wood, J. (1998). Predicting reading comprehension from listening comprehension: Is this the answer to the IQ debate? In C. Hulme & R. M. Joshi (Eds.), *Reading and spelling: Development and disorders* (pp. 319–327). Lawrence Erlbaum Associates.

Joyner, R. E., & Wagner, R. K. (2020). Co-occurrence of reading disabilities and math disabilities: A meta-analysis. *Scientific Studies of Reading: The Official Journal of the Society for the Scientific Study of Reading, 24*(1), 14–22.

Karagiannakis, G., Baccaglini-Frank, A., & Papadatos, Y. (2014). Mathematical learning difficulties subtypes classification. *Frontiers in Human Neuroscience, 8*(7), 1–5.

Kaufmann, L., Mazzocco, M. M., Dowker, A., von Aster, M., Göbel, S. M., Grabner, R. H., et al. (2013). Dyscalculia from a developmental and differential perspective. *Frontiers in Psychology, 4*, 516.

Kaufmann, L., Vogel, S. E., Starke, M., Kremser, C., Schocke, M., & Wood, G. (2009). Developmental dyscalculia: Compensatory mechanisms in left intraparietal regions in response to nonsymbolic magnitudes. *Behavioral and Brain Functions, 5*, 35.

Kearns, D. M., Hancock, R., Hoeft, F., Pugh, K. R., & Frost, S. J. (2019). The neurobiology of dyslexia. *Teaching Exceptional Children, 51*(3), 175–188.

Kim, H., Wang, K., Cutting, L. E., Willcutt, E. G., Petrill, S. A., Leopold, D. R., et al. (2022). The angular gyrus as a hub for modulation of language-related cortex by distinct prefrontal executive control regions. *Journal of Cognitive Neuroscience, 34*(12), 2275–2296.

Kintsch, W. (1988). The role of knowledge in discourse comprehension: A construction-integration model. *Psychological Review, 95*(2), 163–182.

Krinzinger, H., Kaufmann, L., & Willmes, K. (2009). Math anxiety and math ability in early primary school years. *Journal of Psychoeducational Assessment, 27*(3), 206–225.

Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006).

Impaired neural networks for approximate calculation in dyscalculic children: A functional MRI study. *Behavioral and Brain Functions, 2*, Article 31.

Landerl, K., Bevan, A., & Butterworth, B. (2004). Developmental dyscalculia and basic numerical capacities: A study of 8–9-year-old students. *Cognition, 93*(2), 99–125.

Landi, N. (2010). An examination of the relationship between reading comprehension, higher-level and lower-level reading sub-skills in adults. *Reading and Writing: An Interdisciplinary Journal, 23*(6), 701–717.

Landi, N., Frost, S. J., Menc, W. E., Sandak, R., & Pugh, K. R. (2013). Neurobiological bases of reading comprehension: Insights from neuroimaging studies of word level and text level processing in skilled and impaired readers. *Reading & Writing Quarterly: Overcoming Learning Difficulties, 29*(2), 145–167.

Landi, N., & Perfetti, C. A. (2007). An electrophysiological investigation of semantic and phonological processing in skilled and less-skilled comprehenders. *Brain and Language, 102*(1), 30–45.

Landi, N., & Ryherd, K. (2017). Understanding specific reading comprehension deficit: A review. *Language and Linguistics Compass, 11*(2), 1–24.

Learning Disabilities Association of America. (n.d.-a). *New to LD. https://ldaamerica.org/support/new-to-ld*

Learning Disabilities Association of America. (n.d.-b). *Types of learning disabilities. https://ldaamerica.org/types-of-learning-disabilities*

Lervåg, A., Hulme, C., & Melby-Lervåg, M. (2018). Unpicking the developmental relationship between oral language skills and reading comprehension: It's simple, but complex. *Child Development, 89*(5), 1821–1838.

Lewis, C., Hitch, G. J., & Walker, P. (1994). The prevalence of specific arithmetic difficulties and specific reading difficulties in 9- to 10-year-old boys and girls. *Journal of Child Psychology and Psychiatry, and Allied Disciplines, 35*(2), 283–292.

Liberman, I. Y., & Shankweiler, D. (1985). Phonology and the problems of learning to read and write. *Remedial and Special Education, 6*(6), 8–17.

Light, J. G., & DeFries, J. C. (1995). Comorbidity of reading and mathematics disabilities: Genetic and environmental etiologies. *Journal of Learning Disabilities, 28*(2), 96–106.

Lobier, M., & Valdois, S. (2015). Visual attention deficits in developmental dyslexia cannot be ascribed solely to poor reading experience. *Nature Reviews Neuroscience, 16*, 225.

Locascio, G., Mahone, E. M., Eason, S. H., & Cutting, L. E. (2010). Executive dysfunction among children with reading comprehension deficits. *Journal of Learning Disabilities, 43*(5), 441–454.

Lonergan, A., Doyle, C., Cassidy, C., MacSweeney Mahon, S., Roche, R. A. P., Boran, L., et al. (2019). A meta-analysis of executive functioning in dyslexia with consideration of the impact of comorbid ADHD. *Journal of Cognitive Psychology, 31*(7), 725–749.

Lyon, G. R., Shaywitz, S. E., & Shaywitz, B. A. (2003). A definition of dyslexia. *Annals of Dyslexia, 53*(1), 1–14.

Lyons, I. M., Vogel, S. E., & Ansari, D. (2016). On the ordinality of numbers: A review of neural and behavioral studies. *Progress in Brain Research, 227*, 187–221.

MacKinnon McQuarrie, M. A., Siegel, L. S., Perry, N. E., & Weinberg, J. (2014). Reactivity to stress and the cognitive components of math disability in grade 1 children. *Journal of Learning Disabilities, 47*(4), 349–365.

Mammarella, I. C., Ghisi, M., Bomba, M., Bottesi, G., Caviola, S., Broggi, F., et al. (2016). Anxiety and depression in children with nonverbal learning disabilities, reading disabilities, or typical development. *Journal of Learning Disabilities, 49*(2), 130–139.

Marinac, J. V. (2008). *Phonological core dyslexia in secondary school students: Identification and intervention*. Plural Publishing, Inc.

Martin, A., Schurz, M., Kronbichler, M., & Richlan, F. (2015). Reading in the brain of children and adults: A meta-analysis of 40 functional magnetic resonance imaging studies. *Human Brain Mapping, 36*(5), 1963–1981.

Matejko, A. A., & Ansari, D. (2017). How do individual differences in children's domain specific and domain general abilities relate to brain activity within the intraparietal sulcus during arithmetic? An fMRI study. *Human Brain Mapping, 38*(8), 3941–3956.

Mayes, S. D., & Calhoun, S. L. (2006). Frequency of reading, math, and writing disabilities in children with clinical disorders. *Learning and Individual Differences, 16*(2), 145–157.

Mazzocco, M. M. M. (2005). Challenges in identifying target skills for math disability screening and intervention. *Journal of Learning Disabilities, 38*(4), 318–323.

McArthur, G., & Castles, A. (2017). Helping children with reading difficulties: Some things we have learned so far. *Nature Partner Journals: Science of Learning, 2*, 7.

McArthur, G., Castles, A., Kohnen, S., & Banales, E. (2016). Low self-concept in poor readers: Prevalence, heterogeneity, and risk. *PeerJ, 4*, e2669.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences, 7*(7), 293–299.

McKenna, M. C., & Stahl, K. A. D. (2015). *Assessment for reading instruction* (3rd ed.). Guilford Press.

Menon, V. (2016). Working memory in children's math learning and its disruption in dyscalculia. *Current Opinion in Behavioral Sciences, 10*, 125–132.

Menon, V., & Chang, H. (2021). Emerging neurodevelopmental perspectives on mathematical learning. *Developmental Review, 60*, 100964.

Miyashita, Y. (1993). Inferior temporal cortex: Where visual perception meets memory. *Annual Review of Neuroscience, 16*, 245–263.

Monti, M. M., Parsons, L. M., & Osherson, D. N. (2012). Thought beyond language: Neural dissociation of algebra and natural language. *Psychological Science, 23*(8), 914–922.

Morgan, P. L., Farkas, G., Hillemeier, M. M., Mattison, R., Maczuga, S., Li, H., et al. (2015). Minorities are disproportionately underrepresented in special education: Longitudinal evidence across five disability conditions. *Educational Researcher, 44*(5), 278–292.

Morgan, P. L., Li, H., Farkas, G., Cook, M., Pun, W. H., & Hillemeier, M. M. (2017). Executive functioning deficits increase kindergarten children's risk for reading and mathematics difficulties in first grade. *Contemporary Educational Psychology, 50*, 23–32.

Moyer, R. S., & Landauer, T. K. (1967). Time required for judgements of numerical inequality. *Nature, 215*(5109), 1519–1520.

Mussolin, C., De Volder, A., Grandin, C., Schlögel, X., Nassogne, M. C., & Noël, M. P. (2010). Neural correlates of symbolic number comparison in developmental dyscalculia. *Journal of Cognitive Neuroscience, 22*(5), 860–874.

Nation, K., Marshall, C. M., & Snowling, M. J. (2001). Phonological and semantic contributions to children's picture naming skill: Evidence from children with developmental reading disorders. *Language and Cognitive Processes, 16*(2–3), 241–259.

Nation, K., & Snowling, M. J. (1997). Assessing reading difficulties: The validity and utility of current measures of reading skill. *British Journal of Educational Psychology, 67*(3), 359–370.

Nation, K., & Snowling, M. J. (1998). Semantic processing and the development of word-recognition skills: Evidence from children with reading comprehension difficulties. *Journal of Memory and Language, 39*(1), 85–101.

Norton, E. S., Beach, S. D., & Gabrieli, J. D. (2015). Neurobiology of dyslexia. *Current Opinion in Neurobiology, 30*, 73–78.

Oakhill, J. V., & Cain, K. (2000). Children's difficulties in text comprehension: Assessing causal issues. *Journal of Deaf Studies and Deaf Education, 5*(1), 51–59.

Oakhill, J. V., & Cain, K. (2012). The precursors of reading ability in young readers: Evidence from a four-year longitudinal study. *Scientific Studies of Reading, 16*(2), 91–121.

Oakhill, J. V., Hartt, J., & Samols, D. (2005). Levels of comprehension monitoring and working memory in good and poor comprehenders. *Reading and Writing, 18*, 657–686.

Oakhill, J. V., Yuill, N., & Parkin, A. (1986). On the nature of the difference between skilled and less-skilled comprehenders. *Journal of Research in Reading, 9*(2), 80–91.

Ostad, S. A. (1997). Developmental differences in addition strategies: A comparison of mathematically disabled and mathematically normal children. *The British Journal of Educational Psychology, 67(Pt. 3)*, 345–357.

Pammer, K., Hansen, P. C., Kringelbach, M. L., Holliday, I., Barnes, G., Hillebrand, A., et al. (2004). Visual word recognition: The first half second. *NeuroImage, 22*(4), 1819–1825.

Park, J., Li, R., & Brannon, E. M. (2014). Neural connectivity patterns underlying symbolic number processing indicate mathematical achievement in children. *Developmental Science, 17*(2), 187–202.

Parsons, S., & Bynner, J. (2005). *Does numeracy matter more?* National Research and Development Centre for Adult Literacy and Numeracy.

Perfetti, C. A. (1999). Comprehending written language: A blueprint of the reader. In C. Brown & P. Hagoort (Eds.), *The neurocognition of language* (pp. 167–208). Oxford University Press.

Pinel, P., Dehaene, S., Rivière, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *NeuroImage, 14*(5), 1013–1026.

Pinel, P., Le Clec, H. G., Van De Moortele, P. F., Naccache, L., Le Bihan, D., & Dehaene, S. (1999). Event-related fMRI analysis of the cerebral circuit for number comparison. *NeuroReport, 10*(7), 1473–1479.

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage, 10*(1), 15–35.

Price, C. J. (2012). A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. *NeuroImage, 62*(2), 816–847.

Price, C. J., Moore, C. J., Humphreys, G. W., Frackowiak, R. S. J., & Friston, K. J. (1996). The neural regions sustaining object recognition and naming. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 263*(1376), 1501–1507.

Price, G. R., & Ansari, D. (2011). Symbol processing in the left angular gyrus: Evidence from passive perception of digits. *NeuroImage, 57*(3), 1205–1211.

Price, G. R., & Ansari, D. (2013). Developmental dyscalculia. *Handbook of Clinical Neurology, 111*, 241–244.

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology, 17*(24), R1042–R1043.

Price, G. R., & Wilkey, E. D. (2017). Cognitive mechanisms underlying the relation between nonsymbolic and symbolic magnitude processing and their relation to math. *Cognitive Development, 44*, 139–149.

Protopapas, A., Simos, P. G., Sideridis, G. D., & Mouzaki, A. (2012). The components of the simple view of reading: A confirmatory factor analysis. *Reading Psychology, 33*(3), 217–240.

Pugh, K. R., Frost, S. J., Sandak, R., Landi, N., Rueckl, J. G., Constable, R. T., et al. (2008). Effects of stimulus difficulty and repetition on printed word identification: An fMRI comparison of nonimpaired and reading-disabled adolescent cohorts. *Journal of Cognitive Neuroscience, 20*(7), 1146–1160.

Pugh, K. R., Mencl, W. E., Jenner, A. R., Katz, L., Frost, S. J., Lee, J. R., et al. (2001). Neurobiological studies of reading and reading disability. *Journal of Communication Disorders, 34*(6), 479–492.

Richlan, F. (2012). Developmental dyslexia: Dysfunction of a left hemisphere reading network. *Frontiers in Human Neuroscience, 6*, 120.

Richlan, F., Kronbichler, M., & Wimmer, H. (2009). Functional abnormalities in the dyslexic brain: A quantitative meta-analysis of neuroimaging studies. *Human Brain Mapping, 30*(10), 3299–3308.

Rimrodt, S. L., Peterson, D. J., Denckla, M. B., Kaufmann, W. E., & Cutting, L. E. (2010).

White matter microstructural differences linked to left perisylvian language network in children with dyslexia. *Cortex, 46*(6), 739–749.
Ritchie, S. J., & Bates, T. C. (2013). Enduring links from childhood mathematics and reading achievement to adult socioeconomic status. *Psychological Science, 24*(7), 1301–1308.
Robertson, D. A., Gernsbacher, M. A., Guidotti, S. J., Robertson, R. R., Irwin, W., Mock, B. J., et al. (2000). Functional neuroanatomy of the cognitive process of mapping during discourse comprehension. *Psychological Science, 11*(3), 255–260.
Robinson, C. S., Menchetti, B. M., & Torgesen, J. K. (2002). Toward a two-factor theory of one type of mathematics disabilities. *Learning Disabilities Research & Practice, 17*(2), 81–89.
Roe, M. A., Martinez, J. E., Mumford, J. A., Taylor, W. P., Cirino, P. T., Fletcher, J. M., et al. (2018). Control engagement during sentence and inhibition fMRI tasks in children with reading difficulties. *Cerebral Cortex, 28*(10), 3697–3710.
Ryherd, K., Jasinska, K., Van Dyke, J. A., Hung, Y. H., Baron, E., Mencl, W. E., et al. (2018). Cortical regions supporting reading comprehension skill for single words and discourse. *Brain and Language, 186*, 32–43.
Sabatini, J. P., Sawaki, Y., Shore, J. R., & Scarborough, H. S. (2010). Relationships among reading skills of adults with low literacy. *Journal of Learning Disabilities, 43*(2), 122–138.
Schmithorst, V. J., Holland, S. K., & Plante, E. (2006). Cognitive modules utilized for narrative comprehension in children: A functional magnetic resonance imaging study. *NeuroImage, 29*(1), 254–266.
Shalev, R. S., Auerbach, J., Manor, O., & Gross-Tsur, V. (2000). Developmental dyscalculia: Prevalence and prognosis. *European Child & Adolescent Psychiatry, 9*(Suppl. 2), II58–II64.
Shankweiler, D., Lundquist, E., Katz, L., Stuebing, K. K., Fletcher, J. M., Brady, S., et al. (1999). Comprehension and decoding: Patterns of association in children with r7eading difficulties. *Scientific Studies of Reading, 3*(1), 69–94.
Shaywitz, S. E. (2003). *Overcoming dyslexia: A new and complete science-based program of reading problems at any level.* Knopf.
Shaywitz, S. E., Escobar, M. D., Shaywitz, B. A., Fletcher, J. M., & Makuch, R. (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *The New England Journal of Medicine, 326*(3), 145–150.
Shaywitz, S. E., Shaywitz, B. A., Pugh, K. R., Fulbright, R. K., Constable, R. T., Mencl, W. E., et al. (1998). Functional disruption in the organization of the brain for reading in dyslexia. *Proceedings of the National Academy of Sciences of the United States of America, 95*(5), 2636–2641.
Sheuermann, F., & Pedró, F. (Eds.). (2010). Assessing the effects of ICT in education indicators, criteria and benchmarks for international comparisons: Indicators, criteria and benchmarks for international comparisons. *Centre for Educational Research and Innovation* (pp. 21–38). OECD Publishing.
Shum, J., Hermes, D., Foster, B. L., Dastjerdi, M., Rangarajan, V., Winawer, J., et al. (2013). A brain area for visual numerals. *Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 33*(16), 6709–6715.
Siemann, J., & Petermann, F. (2018). Innate or acquired? Disentangling number sense and early number competencies. *Frontiers in Psychology, 9*, 571.
Skagenholt, M., Träff, U., Västfjäll, D., & Skagerlund, K. (2018). Examining the triple code model in numerical cognition: An fMRI study. *PLOS ONE, 13*(6), e0199247.
Snowling, M. J., & Melby-Lervåg, M. (2016). Oral language deficits in familial dyslexia: A meta-analysis and review. *Psychological Bulletin, 142*(5), 498–545.
Soares, N., Evans, T., & Patel, D. R. (2018). Specific learning disability in mathematics: A comprehensive review. *Translational Pediatrics, 7*(1), 48–62.
Spencer, M., Quinn, J. M., & Wagner, R. K. (2014). Specific Reading Comprehension Disability:

Major problem, myth, or misnomer? *Learning Disabilities Research & Practice: A Publication of the Division for Learning Disabilities, Council for Exceptional Children, 29*(1), 3–9.

Spencer, M., & Wagner, R. K. (2018). The comprehension problems of children with poor reading comprehension despite adequate decoding: A meta-analysis. *Review of Educational Research, 88*(3), 366–400.

Steen, L. (1999). Numeracy: The new literacy for a data-drenched society. *Educational Leadership, 57*, 8–13.

Stothard, S. E., & Hulme, C. (1995). A comparison of phonological skills in children with reading comprehension difficulties and children with decoding difficulties. *Child Psychology & Psychiatry & Allied Disciplines, 36*(3), 399–408.

Swanson, H. L., & Jerman, O. (2006). Math disabilities: A selective meta-analysis of the literature. *Review of Educational Research, 76*(2), 249–274.

Swanson, H. L., Zheng, X., & Jerman, O. (2009). Working memory, short-term memory, and reading disabilities: A selective meta-analysis of the literature. *Journal of Learning Disabilities, 42*(3), 260–287.

Tam, Y. P., Wong, T. T., & Chan, W. W. L. (2019). The relation between spatial skills and mathematical abilities: The mediating role of mental number line representation. *Contemporary Educational Psychology, 56*, 14–24.

Temple, E., Poldrack, R. A., Salidis, J., Deutsch, G. K., Tallal, P., Merzenich, M. M., et al. (2001). Disrupted neural responses to phonological and orthographic processing in dyslexic children: An fMRI study. *NeuroReport, 12*(2), 299–307.

Tong, X., Deacon, S. H., & Cain, K. (2014). Morphological and syntactic awareness in poor comprehenders another piece of the puzzle. *Journal of Learning Disabilities, 47*, 22–33.

Ullman, M. T. (2004). Contributions of memory circuits to language: The declarative/procedural model. *Cognition, 92*, 231–270.

Van den Broek, P., Young, M., Tzeng, Y., & Linderholm, T. (1999). The Landscape model of reading: Inferences and the online construction of memory representation. In H. Van Oostendorp & S. R. Goldman (Eds.), *The construction of mental representations during reading* (pp. 71–98). Lawrence Erlbaum Associates.

Vellutino, F. R., Tunmer, W. E., Jaccard, J. J., & Chen, R. (2007). Components of reading ability: Multivariate evidence for a convergent skills model of reading development. *Scientific Studies of Reading, 11*(1), 3–32.

Vinckier, F., Dehaene, S., Jobert, A., Dubus, J. P., Sigman, M., & Cohen, L. (2007). Hierarchical coding of letter strings in the ventral stream: Dissecting the inner organization of the visual word-form system. *Neuron, 55*(1), 143–156.

von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology, 49*(11), 868–873.

Vuilleumier, P., Ortigue, S., & Brugger, P. (2004). The number space and neglect. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior, 40*(2), 399–410.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*(2), 192–212.

Waldie, K. E. (2002). Reading with the right hemisphere: From normal development to dysphonetic dyslexia. In S. P. Shohov (Ed.), *Advances in psychology research* (pp. 157–183). Nova Science.

Waldie, K. E., Haigh, C., Badzakova-Trajkov, G., Buckley, J., & Kirk, I. (2013). Reading the wrong way with the right hemisphere. *Brain Sciences, 3*(4), 1060–1075.

Walenski, M., Europa, E., Caplan, D., & Thompson, C. K. (2019). Neural networks for sentence comprehension and production: An ALE-based meta-analysis of neuroimaging studies. *Human Brain Mapping, 40*(8), 2275–2304.

Wang, K., Banich, M. T., Reineberg, A. E., Leopold, D. R., Willcutt, E. G., Cutting, L. E., et al. (2020). Left posterior prefrontal regions support domain-general executive processes needed for both reading and math. *Journal of Neuropsychology, 14*(3), 467–495.

What Works Clearinghouse. Institute of Education Sciences. *https://ies.ed.gov/ncee/wwc.*

Wilkey, E. D., Barone, J. C., Mazzocco, M. M. M., Vogel, S. E., & Price, G. R. (2017). The effect of visual parameters on neural activation during nonsymbolic number comparison and its relation to math competency. *NeuroImage, 159*, 430–442.

Wilkey, E. D., Pollack, C., & Price, G. R. (2020). Dyscalculia and typical math achievement are associated with individual differences in number-specific executive function. *Child Development, 91*(2), 596–619.

Wilkey, E. D., & Price, G. R. (2019). Attention to number: The convergence of numerical magnitude processing, attention, and mathematics in the inferior frontal gyrus. *Human Brain Mapping, 40*(3), 928–943.

Willcutt, E. G., & Pennington, B. F. (2000). Psychiatric comorbidity in children and adolescents with reading disability. *Journal of Child Psychology and Psychiatry, 41*(8), 1039–1048.

Wilson, A. J., & Dehaene, S. (2007). Number sense and developmental dyscalculia. In D. Coch, G. Dawson, & K. W. Fischer (Eds.), *Human behavior, learning, and the developing brain: Atypical development* (pp. 212–238). Guilford Press.

Wimmer, H., Schurz, M., Sturm, D., Richlan, F., Klackl, J., Kronbichler, M., et al. (2010). A dual-route perspective on poor reading in a regular orthography: An fMRI study. *Cortex, 46*(10), 1284–1298.

Yang, X., Li, H., Lin, N., Zhang, X., Wang, Y., Zhang, Y., et al. (2019). Uncovering cortical activations of discourse comprehension and their overlaps with common large-scale neural networks. *NeuroImage, 203*, 116200.

Yarkoni, T., Poldrack, R. A., Nichols, T. E., Van Essen, D. C., & Wager, T. D. (2011). Large-scale automated synthesis of human functional neuroimaging data. *Nature Methods, 8*(8), 665–670.

Yeniad, N., Malda, M., Mesman, J., Van IJzendoorn, M. H., & Pieper, S. (2013). Shifting ability predicts math and reading performance in children: A meta-analytical study. *Learning and Individual Differences, 23*, 1–9.

Yeo, D. J., Wilkey, E. D., & Price, G. R. (2017). The search for the number form area: A functional neuroimaging meta-analysis. *Neuroscience and Biobehavioral Reviews, 78*, 145–160.

Yuill, N., & Oakhill, J. V. (1991). *Children's problems in text comprehension: An experimental investigation.* Cambridge University.