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Developmental dyscalculia as a heterogeneous disability

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Numerical cognition is essential to many aspects of life and arithmetic abilities predict academic achievements better than reading (Estrada, Martin-Hryniewicz, Peek, Collins, & Byrd, 2004). Acquiring a solid sense of numbers and being able to mentally manipulate numbers are at the heart of this ability. Research suggests that infants already show a basic perception of quantities. However, a long, effortful, and sometimes painful developmental process is required until a child acquires the numerical representations in the adult sense (Butterworth, 2005). Studying arithmetic may be extremely difficult for those who suffer from specific learning disabilities in arithmetic, henceforth termed developmental dyscalculia (DD). Children with poor numeracy are at a disadvantage in both academic and everyday life situations (e.g., handling money). Adults with poor numeracy are more than twice as likely to be unemployed as those with competent numeracy (Parsons & Bynner, 1997; Rivera-Batiz, 1992). Poor numeracy often means low financial literacy with negative

consequences for economic well-being. Estimates of prevalence of DD vary according to the definition of the disability but for the relatively isolated difficulty, estimates are between 3% and 6% (Gross-Tsur, Manor, & Shalev, 1996; Lewis, Hitch, & Walker, 1994; Shalev & Gross-Tsur, 2001) and are comparable to estimates of learning disability in reading.

Research on DD is characterized by various trends: the study of high-level school-like concepts vs. low-level processes (e.g., enumeration), or the study of domain-general (e.g., attention) vs. domain-specific (e.g., number sense) factors. These research trends give rise to different notions about difficulties in numerical cognition and their roots. Whether DD might be an isolated deficiency or not (see Rubinsten & Henik, 2009), it is clear that similar to other learning disabilities, DD is rarely a very pure (e.g., Ashkenazi & Henik, 2010a, 2010b) disorder. In most cases, children and adults who suffer from DD present difficulties in areas or mental processes different from pure numerical deficiencies.

The current chapter discusses heterogeneous aspects of DD both in terms of behavior and cognitive operations and in terms of the neural structures that underlie the deficiency.

Characteristics of DD

Children with DD are far behind their classmates in a wide range of numerical tasks: they have difficulties in retrieval of arithmetical facts (Geary, 1993; Geary & Hoard, 2001; Ginsburg, 1997; Russell & Ginsburg, 1984), in using arithmetical procedures (Russell & Ginsburg, 1984; Shalev & Gross-Tsur, 2001), and use immature problem-

solving strategies—for example, using finger counting (Jordan, Hanich, & Kaplan, 2003)—at an age when their classmates have already stopped using such strategies. Many studies have been directed at higher-level, school-like concepts. Hence, research has focused on general cognitive functions such as poor working memory (Geary, 1993), deficits in attention systems (Shalev, Auerbach, & Gross-Tsur, 1995), disorders of visuo-spatial functioning (Bull, Johnston, & Roy, 1999), and deficiencies in the retrieval of information (e.g., arithmetic facts) from memory (Kaufmann, Lochy, Drexler, & Semenza, 2004). In recent years another trend toward identifying low-level deficits in DD has been advocated. Such research aims at revealing the building blocks of numerical cognition and the very basic deficiencies that underlie DD (Ansari & Karmiloff-Smith, 2002). Efforts in this direction revealed difficulties in subitizing (Ashkenazi, Mark-Zigdon, & Henik, 2013; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Schleifer & Landerl, 2011) and counting (Geary, Bow-Thomas, & Yao, 1992; Geary, Hoard, & Hamson, 1999; Landerl, Bevan, & Butterworth, 2004), in comparative judgment of both symbolic (Ashkenazi, Mark-Zigdon, & Henik, 2009; Mussolin, Mejias, & Noël, 2010) and non-symbolic (Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007) stimuli, and in automatic processing of numbers (Cohen Kadosh et al., 2007; Rubinsten & Henik, 2005). The latter led to a view of an innate, domain-specific foundation of arithmetic and to the suggestion that arithmetic disability involves a domain-specific deficit in the capacity to enumerate (Butterworth, 2010).

However, several findings suggest that this view needs to be examined carefully: 1) arithmetic seems to rely on both domain-specific and domain-general abilities; 2) in many cases behaviors as well as cognition of DD could be characterized by deficits in

other areas such as attention or memory and not only as a number sense deficiency; and 3) studies of the neural structures involved in DD reveal areas and mechanisms that hint toward heterogeneous damage. Figure 1 presents several cognitive deficiencies, involving various brain mechanisms, which might contribute to different manifestations of DD.

<see Figure 1>

Symbolic vs. non-symbolic representations

There is a continuous debate in the scientific literature about the ability of people with DD to represent symbolic and non-symbolic numerical information. Specifically, symbolic numerical information involves number words such as "four", "ten", or "plus"; or written numerical symbols such as "4", "10", or "+". Non-symbolic numerical information automatically extracts the understanding of the approximate quantity of concrete sets of objects (such as visual dots). Core knowledge of numbers is essentially non-symbolic. Symbolic numerical information, on the other hand, varies across cultures and is influenced by language. Numerical symbols, once acquired, become attached to their non-symbolic numerical representations. Accordingly, during development links between symbols and quantities should become automatic (for review see Ansari, 2008). There are disagreements regarding the question of whether DD is the result of deficits in non-symbolic numerical representations (e.g., Butterworth, 2010), in symbolic numerical representations (e.g., Mussolin et al., 2009), in the ability to access numerical meaning (i.e., non-symbolic information) from symbols (e.g., Rousselle & Noël, 2007), or in the ability to

automatically link symbolic and non-symbolic representations (e.g., Rubinsten & Henik, 2005).

The existent developmental brain imaging literature on DD, in regard to non-symbolic number processing (e.g., comparing the numerosity of two groups of dot patterns), is inconclusive. Researchers reported both group differences between children with and without DD in their ability to process non-symbolic numerical information (e.g., Price et al., 2007) and the absence of group differences (e.g., Kucian et al., 2006). However, even when using a symbolic comparison task, deficits in basic magnitude representation or quantity processing may appear. For example, Soltész and colleagues (Soltész, Szűcs, Dékány, Márkus, & Csépe, 2007), who examined symbolic comparison, found that adolescents with DD show no late event-related brain potentials (ERPs) distance effect between 400 and 440 ms on right parietal electrodes when comparing Arabic numerals. Such a finding may indicate that the processing of the magnitudes of numerical information is abnormal in DD. In addition, Mussolin and colleagues (Mussolin et al., 2009) found that compared to typically developing children, the numerical distance effect does not modulate intraparietal sulcus (IPS) activation in 9- to 11-year-old children with DD during a symbolic numerical comparison task. According to the authors, the IPS, which is typically involved with numerical representations, may be deficient in DD.

Only a few studies have investigated performance of DD participants in non-symbolic comparisons. Price and colleagues (Price et al., 2007), for example, found differences between DD participants and controls in non-symbolic comparisons in an fMRI study. Specifically, the difference was found in brain activation but not in response time.

Also, they found a weak IPS activation in DD children compared to controls when they compared non-symbolic numerical stimuli. Moreover, Landerl and colleagues (Landerl, Fussenegger, Moll, & Willburger, 2009) found that 8- to 10-year-old DD children were slower than controls in both symbolic and non-symbolic number comparisons. Mussolin, Mejias, and Noel (2010) found that 10- and 11-year-old children with DD showed a larger distance effect in both symbolic and non-symbolic numerical comparisons, suggesting a deficit in the ability to process numerical magnitudes. Other studies with DD populations suggest that those with DD may be deficient in their ability to automatically associate between written digits (e.g., the symbol "3") and their corresponding quantities (e.g., the quantity of 3 items). Indeed, several studies support this weak-link theory by showing that there is actually an association between these two systems (Libertus, Waldorff, & Brannon, 2007; Notebaert, Nelis, & Reynvoet, 2011; Piazza, Pinel, Le Bihan, & Dehaene, 2007) and that it might be deficient in DD participants (Rousselle & Noël, 2007; Rubinsten & Henik, 2005) (although see Mussolin et al., 2009). Recently, in a review paper, Noël and Rousselle (2011) argued that the first deficit shown in those with DD appears in exact/symbolic numerical representations during the process of learning the symbolic numerical system. Deficiencies in non-symbolic numerical representations appear only later and are secondary to the first deficit.

Nonetheless, there is an increasing awareness that the core deficit approach—which implies a single-deficit view of DD (e.g., deficient non-symbolic representations)—is not sufficient to account for the complex and often heterogeneous clinical picture of the disorder (Kaufmann & Nuerk, 2005; Rubinsten, 2009; Rubinsten & Henik, 2009). Such an argument fits with findings showing that 20%-60% of children with DD have

associated learning problems such as dyslexia (Mayes & Calhoun, 2006; Dirks, Spyer, van Lieshout, & de Sonneville, 2008) or attention deficit/hyperactivity disorder (Capano, Minden, Chen, Schachar, & Ickowicz, 2008; von Aster & Shalev, 2007).

Dyslexia comorbidity and the role of the angular gyrus

In a German sample of children (n = 378) (reported by von Aster and Shalev, 2007), researchers found that although the prevalence of dyscalculia was about 6%, only 1.8% had pure dyscalculia, while 4.2% had co-morbid dyslexia. In conjunction with Noël and Rousselle's (2011) argument, it may be suggested that the ability to automatically associate written symbols with mental representations such as quantities or phonemes may lead to both math and reading difficulties, which are quite common. Such deficits are not conclusively proven scientifically, but they can serve as a basis for testable predictions at both the behavioral and the biological levels.

It is clear that the resolution of the debate concerning the extent to which arithmetic impairments are specific to DD or shared with dyslexia is challenged by the marked heterogeneity in behavioral symptoms in both dyslexia and DD (Simmons & Singleton, 2008; Tressoldi, Rosati, & Lucangeli, 2007; von Aster & Shalev, 2007). As can be seen in Figure 1, it is not clear if the deficit in math, for example, is the result of a reading deficit (i.e., dyslexia) or is unique to the numerical faculty. In the last two decades, research has made impressive strides forward in studying numerical cognition and brain mechanisms involved in DD by using focused, low-level cognitive tasks (e.g., the numerical Stroop task) that resulted in a detailed description of the cognitive deficit; this was instead of or in addition to the paper and pencil tasks, which could not give an exact description of the deficit. Recently, for example, a

double dissociation between DD and dyslexia was found in the ability to automatically associate quantities with written numbers vs. automatically associating phonemes with written letters (Rubinsten & Henik, 2006). Only a few studies used similar low-level tasks to address co-morbidity issues. Landerl and colleagues (Landerl et al., 2004) argued that children with DD and DD+dyslexia do not have a different type of deficit but suffer from the same number-processing deficit. Both groups of children, with DD only and DD+dyslexia, were slower on tests that included counting dots, comparing values of single digits, reciting number sequences, reading three-digit numbers, and writing numbers. Later, Landerl and colleagues (Landerl et al., 2009) examined a group of children with DD only, a group of children with dyslexia only, and a DD+ dyslexia group. A phonological deficit was found in both dyslexia groups, regardless of numerical deficits, but not in the DD group. However, deficits in processing of symbolic and non-symbolic numerical information were found in the two DD groups, regardless of reading difficulties. Rousselle and Noël (2007) found no evidence for differential patterns of performance between children with DD and DD+dyslexia in tasks assessing basic numerical skills. However, others (Jordan et al., 2003; Jordan, Kaplan, & Hanich, 2002) suggested that children with only DD have better numerical performance than children with DD+dyslexia in domains of arithmetic such as verbal problem solution and calculations.

Let us suggest a hypothesis for such a DD+dyslexia co-morbidity: One neural candidate that may be involved with both DD and dyslexia is the angular gyrus (and not necessarily the IPS). The angular gyrus (AG) is considered to be involved in integration of semantic information into an ongoing context (Humphreys, Binder,

Medler, & Liebenthal, 2007), in associating symbols with non-symbolic events, such as written letters with sounds (i.e., phonemes) (Booth et al., 2004), and it was found to be recruited to a lesser extent in dyslexic children (Pugh et al., 2000) than in non-dyslexic children. This suggestion appears in Figure 1B. Note, that the AG is deactivated most of the time rather than activated during numerical tasks (Wu et al., 2009) and the activity level of the AG is modulated similarly after arithmetical and non-arithmetical training (i.e., figural-spatial task (Grabner, Ischebeck et al., 2009)). Our idea is in line with the suggestion that the left AG is involved in general processes of (fact) learning, skilled retrieval, and level of automatisation (see Zamarian and Delazer, this volume).

Also, the left AG and/or surrounding perisylvian brain regions show larger activation during exact calculation that depends on instruction and often relies on verbal rote memorizing (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Lee, 2000; Venkatraman, Siong, & Chee, 2006; Zago, Turbelin, Vigneau, & Tzourio-Mazoyer, 2008; but see Rusconi, Walsh, & Butterworth, 2005, who found that the left AG is not essential for the storage of multiplication and addition facts). Specifically, the AG is involved in calculation (Grabner, Ansari, et al., 2009; van Harskamp, Rudge, & Cipolotti, 2002), in retrieving simple arithmetic facts such as 2 X 3 = 4 (Dehaene, Molko, Cohen, & Wilson, 2004), in transfer of mental operations (between multiplication and division (Ischebeck, Zamarian, Schocke, & Delazer, 2009), in mental representations of magnitudes or quantities (Göbel, Walsh, & Rushworth, 2001; Rusconi et al., 2005), and also in visuo-spatial attention that is induced by the mental number line (Cattaneo, Silvanto, Pascual-Leone, & Battelli, 2009). In addition, and with relevance to the current work, Kaufmann and colleagues (Kaufmann et al.,

2006) tested participants in a numerical Stroop task that required them to focus on one stimulus dimension (numerical value or physical size) and to ignore the other. Stimuli were classified into three categories: 1) congruent: physical and numerical comparison leads to the same response (e.g. 3 4); 2) incongruent: physical and numerical comparison leads to different responses (e.g. 3 4); and 3) neutral: the stimuli differ only with regard to the task-relevant stimulus property (e.g. 3 4 for numerical comparison). The results indicated that in the numerical comparisons, but not in physical comparisons, the left AG was activated (together with IPS and the supramarginal gyrus bilaterally). The activation of the AG was suggested to reflect the retrieval of numerical information that is associated with the number symbols, while this was not required in the physical task. This may be similar to the involvement of the AG with associating written letters with phonemes. Hence, deficit in this structure may cause both reading impairments and calculation difficulties. Accordingly, it is reasonable to suggest that any lesion in the left AG could lead to calculation difficulties that result from either one or more of the following: 1) deficits in the ability to associate mental representations (e.g., quantities or phonemes) with symbols (e.g., written numbers or letters), and 2) deficits in the ability to retrieve simple arithmetic facts from verbal memory. As suggested by Rousselle and Noël (2007), such an AG developmental delay or deficit may lead to deficiencies in the symbolic system but also to co-morbidities such as DD and dyslexia.

Attention and working memory

Studies indicate that those with DD have attention deficits, such as impaired executive attention or visuo-spatial attention and alertness (Ashkenazi & Henik, 2010a, 2010b). In recent years, various laboratories have been engaged in studying networks of

attention by using the Attention Network Test—ANT (Fan, McCandliss, Sommer, Raz, & Posner, 2002) or various adaptations of this test (e.g., ANTI; Callejas, Lupiáñez, & Tudela, 2004). The ANT and similar tests were designed to examine three aspects of attention: executive function, alertness, and orienting. Executive control or selective attention is central to goal-directed behavior. It is commonly studied by employing conflict situations like the Stroop or the flanker tasks. In such tasks one stimulus or dimension is relevant and other stimuli or dimensions are irrelevant. Participants are asked to pay attention to the relevant and ignore the irrelevant features of the stimuli. It has been suggested that these conflict situations involve the frontal lobe, mostly the midline frontal areas (anterior cingulate cortex) and the lateral prefrontal cortex (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). The alerting network is related to the awakeness state. Its role is to activate and preserve attention. The alerting network is based on the distribution of the brain norepinephrine system, and sustains attention during long-lasting monotonic tasks (Posner & Petersen, 1990). The orienting network is involved in moving attention to a specific location in space (Posner & Petersen, 1990). Ashkenazi and Henik (2010a) examined participants suffering from pure DD (without any comorbidity and specifically without ADHD) and reported deficits in the alerting and executive networks. Specifically, DD participants showed a larger alerting effect and a larger congruity effect compared to matched controls. Furthermore, visuo-spatial attention deficits were found in the DD participants in a physical line bisection task. Non-deficit participants usually present a small leftward bias during the bisection of a physical line (pseudoneglect). Pseudoneglect is considered to be based on an asymmetry in visuo-spatial attention processing between the brain cerebral hemispheres, where the right hemisphere is strongly involved in attention processing.

In contrast with non-deficit participants, those with DD had no consistent bias in the bisection of the physical line. This result implies a difficulty in visual and spatial attention (Ashkenazi & Henik, 2010a, 2010b).

The results described above suggest that those with DD suffer from deficits in various aspects of attention. Moreover, numerical processing deficits in DD may involve attention or other domain-general mechanisms. For example, DD participants have shown an impaired behavioral facilitation component in the numerical Stroop task (Rubinsten & Henik, 2005). As mentioned above, the lack of facilitation in the size congruity effect in DD participants was explained by a weakness in the automatic connections between Arabic numeral and the internal magnitude representation. However, the size congruity effect, which is characteristic of the numerical Stroop task, is modulated by: 1) interactions between quantity and size (Cohen Kadosh et al., 2005; Cohen Kadosh, Lammertyn, & Izard, 2008), and 2) executive attention (Derrfuss, Brass, Neumann, & von Cramon, 2005). Importantly, a manipulation of cognitive load during the numerical Stroop task eliminated the facilitation component in typically developed adults. A similar pattern was presented by participants suffering from DD, in the task without the executive load (Ashkenazi, Rubinsten, & Henik, 2009). Furthermore, an event-related potential (ERP) study examined the numerical distance effect among those with DD. The results showed an early indication for a distance effect that was similar between DD and control participants (between 200 and 300 ms). However, a late right parietal distance effect, between 400 and 440 ms, was not evident in the DD group. This hints that DD impairments in number processing can be based on decelerated executive functioning weakness rather than a lack of automatic quantity activations (Szűcs & Soltész, 2007).

Another hypothesis is that pure DD is related to deficits in visuo-spatial attention (Ashkenazi & Henik, 2010a, 2010b) or visuo-spatial working memory (Rotzer et al., 2009). The basis for this hypothesis is that the IPS is believed to support a spatial representation of a mental number line, which requires visuo-spatial working memory and attention (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002). Furthermore, the IPS is strongly involved in working memory and specifically, in visuo-spatial working memory and spatial attention (Simon et al., 2002). Consistent with a visuo-spatial working memory deficit, it has been shown that those with DD have behavioral deficits in visuo-spatial working memory, as well as decreased activity in the IPS, right insula, and the right inferior frontal gyrus (IFG) relative to control participants during a visuo-spatial working memory task (Rotzer et al., 2009).

One fundamental question related to attentional deficits in DD is whether a domain-general weakness is the core of DD or just a co-occurrence? If a core of DD is attention weakness then targeted attention training should improve numerical processing in DD. However, attentional training improved most of the attentional deficits of those with DD, but it did not improve the abnormalities of the DD group in arithmetic or basic numerical processing. Thus, the deficits in attention among those with DD and the deficits in numerical processing may originate from different sources, or from a the same source, at earlier developmental stages, that is going through cognitive and neural specialization as a function of development (Ashkenazi & Henik, 2012) (see Figure 1C).

A major attention deficit is attention-deficit/hyperactivity disorder (ADHD). ADHD, which affects 4% to 10% of school-aged children (Skounti, Philalithis, & Galanakis, 2006) is associated with substantial academic underachievement in mathematics and reading (Spira & Fischel, 2005). For example, recent estimates suggest that 25% of children with ADHD have a comorbid disorder of mathematics (Mayes & Calhoun, 2006). The range and nature of mathematical difficulties associated with ADHD are unclear, primarily because of lack of data. A substantial proportion of individuals with ADHD manifest unexpected problems in mathematics that cause an impairment in academic achievement and daily functioning, with estimates ranging from 10% to 60% (Capano et al., 2008; Mayes, Calhoun, & Crowell, 2000). Specifically, existing studies indicate that children with ADHD exhibit problems in completing arithmetic calculations quickly and accurately (Barry, Lyman, & Klinger, 2002; Benedetto-Nasho & Tannock, 1999), and that these problems may persist into adulthood (Biederman et al., 2005; Biederman, Monuteaux, & Coyle, 2004). The rates of co-occurrence of mathematical difficulties and ADHD are greater than the rates of either math difficulties or ADHD alone in the general population (Shalev, 2004), but the underlying mechanisms for the overlap between ADHD and mathematical difficulties are unknown. Some researchers attribute the significant mathematical delays in children with ADHD to attention-based impairments (Lindsay, Tomazic, Levine, & Accardo, 2001) or working memory (Rosselli, Matute, Pinto, & Ardila, 2006).

These general cognitive impairments (i.e., not specific to mathematics) are considered to be integral features of both the DD and the ADHD syndrome and hence, may cause mathematical difficulties in some of these children (i.e., DD+ADHD) (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006). An alternative proposition is that

subgroups of children with ADHD and mathematical difficulties may exhibit different underlying mechanisms, including specific deficits in basic numerical processing (e.g., quantity processing), as is manifest in children with DD (i.e., two major cognitive deficits resulting in DD+ADHD). Rubinsten and colleagues (Rubinsten, Bedard, & Tannock, 2008) investigated effects of stimulant medication (methylphenidate; MPH) on arithmetic performance in children with ADHD. They identified three groups of children with ADHD from an existing large data base: one group with DD (DD+ADHD), one group with more general and less severe difficulties in arithmetic—mathematic learning difficulty MLD—(MLD+ADHD), and one group with good arithmetic abilities (ADHD). Children with DD+ADHD exhibited both general cognitive dysfunctions and specific deficits in understanding quantities. In contrast, arithmetic difficulties in children with MLD+ADHD were associated with deficits in executive function and working memory. Furthermore, MPH enhanced performance in arithmetic problems dependent upon working memory (involving activation in the frontal lobes) but not upon processing numerical quantity (involving activation in the parietal lobes). These findings suggest the importance of distinguishing between DD+ADHD and MLD+ADHD. Namely, in some of the children, ADHD impairments in attention or working memory also caused mathematical difficulties resulting in co-occurrence of MLD. Figure 1D presents a possible case in which a deficient executive attention, due to a deficit to the frontal lobe, produces difficulties in arithmetic and in attention. The latter appears as ADHD.

In contrast, cases of DD+ADHD may be the result of double deficits in both quantity processing and executive functions. It should be noted that Kaufmann and colleagues have found that some 9- to 12-year-old children with ADHD (with no other

developmental disorder) have deficient numerical processing skills, specifically in their ability to process numerical magnitude (Kaufmann & Nuerk, 2008).

Neuroanatomy of DD

The previous discussions involved all levels of analyses—behavioral, cognitive, and neuro-anatomical. Here we aim to provide a holistic view on the neuroanatomical model of DD (see also Kucian et al., this volume).

Converging evidence from infant, primates, and adults indicates that an a-modal, domain-specific representation of approximate quantities is supported by the IPS in the posterior parietal cortex (Cohen Kadosh et al., 2008; Dehaene, Piazza, Pinel, & Cohen, 2003). Hence, it is not surprising that the IPS has been suggested as the source of vulnerability in DD (Butterworth, Varma, & Laurillard, 2011). Most of the studies that investigated brain activity in those with DD concentrated on basic numerical processing tasks (Kaufmann et al., 2009; Kucian, Loenneker, Martin, & von Aster, 2011; Mussolin et al., 2009; Price et al., 2007). The majority of these studies have shown decreased activity in the IPS in participants that were diagnosed as having DD compared to control participants (Mussolin et al., 2009; Price et al., 2007). Specifically, a reduced numerical distance effect was found in the right IPS in non-symbolic (Price et al., 2007, but see reports by Kaufmann et al., 2009, and Kucian et al., 2011), and symbolic number comparison (Mussolin et al., 2009). Furthermore, a behavioral deficit in the retrieval of arithmetical facts is one of the most reported behavioral deficits in DD (Geary, 2004; Geary et al., 1992; Gross-Tsur et al., 1996). Hence, weakness in the right IPS activity was found also during high-level arithmetical problem solution in the DD population compared to matched controls

(Ashkenazi, Rosenberg-Lee, Tenison, & Menon, 2012). Interestingly, structural neuroanatomical data of the DD population also points to the right IPS as a location of lower gray matter density in the DD group compared to controls (Rotzer et al., 2008; Rykhlevskaia, Uddin, Kondos, & Menon, 2009). Another support for the involvement of the right IPS in DD comes from a transcranial magnetic stimulation (TMS) study. Specifically, a magnetic pulse to the right IPS in typically developed adults resulted in DD-like size congruity effect (Cohen Kadosh et al., 2007).

However, the isolated involvement of the IPS in number processing is questionable. Moreover, it is widely accepted that networks of domain-general brain regions distributed across the cortex serve arithmetic and basic numerical processing. For example, a recent meta-analysis examining adult data indicated that visual areas, such as the fusiform gyrus, as well as multiple regions of the prefrontal cortex (such as the dorsolateral prefrontal cortex−DLPFC−and the IFG), are consistently active across different numerical and arithmetical tasks, and reflected in domain-general demands (Arsalidou & Taylor, 2011). Specifically, the IFG is thought to play a role in visual working memory necessary for arithmetic processing (Song & Jiang, 2006), while the bilateral DLPFC is believed to underlie attention and task difficulty during calculation tasks (Zago et al., 2008; Zhou, Zang, Dong, Qiao, & Gong, 2007). Moreover, both the right IFG and DLPFC are involved in tasks that require executive functions like stopping an incipient response and ignoring irrelevant distractors, respectively (Botvinick, Cohen, & Carter, 2004; Kalanthroff, Goldfarb, & Henik, 2013; Verbruggen & Logan, 2008).

In relation to the DD population, in addition to decreased activity and lower gray matter density in the IPS, individuals with DD have also shown abnormal activity patterns and abnormal structure in frontal, and visual brain regions (Ashkenazi et al., 2012; Mussolin et al., 2009; Price et al., 2007; Rotzer et al., 2008; Rykhlevskaia et al., 2009). Specifically, a reduced numerical distance effect was found in the DD population compared to the typical population, in frontal brain regions during symbolic and non-symbolic numerical comparisons (Mussolin et al., 2009; Price et al., 2007). Similarly, a reduced numerical distance effect was found in the left-hemisphere fusiform gyrus (Price et al., 2007, but see a recent report by Kucian et al., 2011). Moreover, children with DD showed lower arithmetical complexity task modulation than controls during arithmetical problem solution. Specifically, typical participants showed increased activity level in prefrontal and bilateral fusiform gyrus brain regions with increased arithmetical complexity. In contrast, the DD group showed the same level of activity regardless of the arithmetic complexity level (Ashkenazi et al., 2012). Studies of brain morphometry and tractography in those with DD have also provided evidence for abnormalities of white and gray matter in frontal regions (Rotzer et al., 2008), and the right fusiform and parahippocampal gyri, and cerebellum (Rykhlevskaia et al., 2009). Furthermore, deficiencies in right hemisphere micro-structure and long-range white matter projection fibers linking the right fusiform gyrus with the temporal-parietal region were also deficient in those with DD (Rykhlevskaia et al., 2009). Note that a recent meta-analysis of fMRI studies (Kaufmann, Wood, Rubinsten, & Henik, 2011) revealed that children recruit distributed networks encompassing parietal and frontal regions bilaterally. Namely, activation differences between children with and without dyscalculia were observed not only in number-relevant parietal regions but also in the frontal and occipital

cortex. Taken together, imaging studies on DD point to domain-specific weakness in designated numerical processing regions (such as the right IPS), as well as weakness in multiple frontal, visual, and middle temporal regions and fiber tracks connecting those regions. This fits in with the findings suggesting involvement of domain-general processes in the etiology of DD, multiple behavioral symptoms, and potential comorbidity.

Conclusion

Parents, clinicians, and researchers are aware that homogeneity of symptoms is not as common as expected and heterogeneity of manifestations of a deficiency is not an exception. We (Henik, Rubinsten, & Ashkenazi, 2011; Rubinsten & Henik, 2009, 2010) have recently argued that core features of mental disorders are best understood in terms of deficits at the cognitive and the biological levels. Specifically: 1) core (''common cause'') deficits at the cognitive or brain level may show up as a network of symptoms even when there is a single deficit (Karmiloff-Smith, 1998); and 2) a single deficit at the behavioral or cognitive level may produce, through development, a cascade of difficulties that may end up as a network of symptoms at the behavioral level. Exploring the heterogeneity of DD and domain general weakness will potentially result in individual-level and targeted intervention programs for the remediation of DD (Cohen Kadosh, Dowker, Heine, Kaufmann, & Kucian, in press). Future research needs to examine heterogeneity in disability as part and parcel of the deficiency. Figure 1 gives several relevant examples.
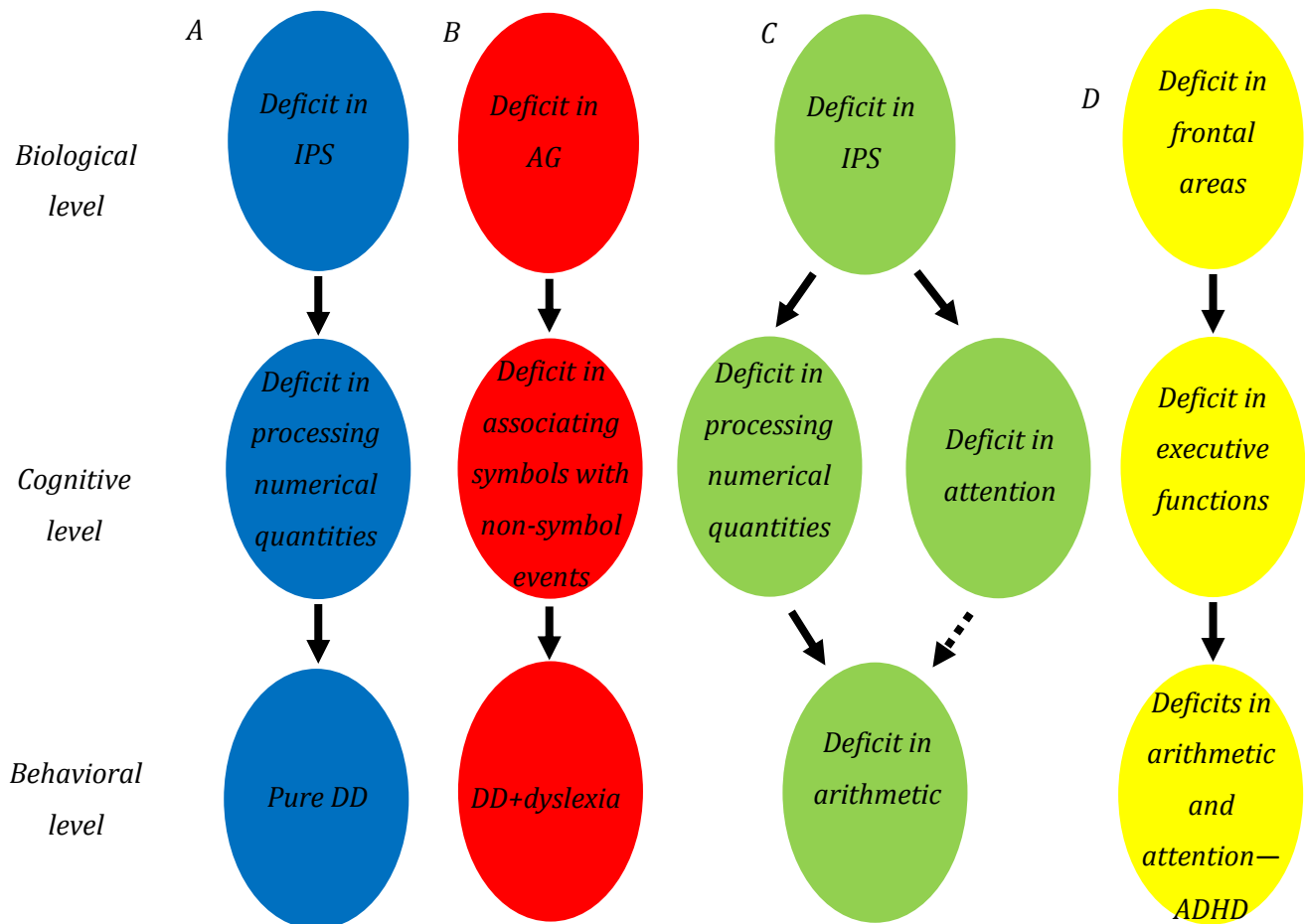
Figure 1

A) Deficit in IPS leads to a pure deficit in numerical processing only, and results in pure DD. B) Deficit to the AG leads to deficits in associating symbols with the events they symbolize. This, in turn, leads to difficulties both in language and DD. C) Deficit in IPS leads to a deficit in processing numerical quantities and to a deficit in attention. Both numerical and attention deficits may create a deficit in arithmetic processing. The dashed line between the deficit in attention at the cognitive level and the deficit in arithmetic at the behavioral level suggests that the attention deficit might exist but contribute only minimally to the arithmetic deficit. D) Deficit in frontal lobe leads to

deficient executive functions and, in turn, to a deficit in arithmetic and in attention. The latter is indicated in ADHD.

Acknowledgement

References

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews Neuroscience, 9*, 278-291.

Ansari, D., & Karmiloff-Smith, A. (2002). Atypical trajectories of number development: a neuroconstructivist perspective. *Trends in Cognitive Sciences, 6*, 511-516.

Arsalidou, M., & Taylor, M. J. (2011). Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. *NeuroImage, 54*, 2382-2393.

Ashkenazi, S., & Henik, A. (2010a). Attentional networks in developmental dyscalculia. *Behavioral and Brain Functions, 6:2*, 1-12. doi: 10.1186/1744-9081-6-2

Ashkenazi, S., & Henik, A. (2010b). A disassociation between physical and mental number bisection in developmental dyscalculia. *Neuropsychologia, 48*, 2861-2868.

Ashkenazi, S., & Henik, A. (2012). Does attentional training improve numerical processing in developmental dyscalculia? *Neuropsychology, 26*, 45-56.

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2009). Numerical distance effect in developmental dyscalculia. *Cognitive Development, 24*, 387-400.

Ashkenazi, S., Mark-Zigdon, N., & Henik, A. (2013). Do subitizing deficits in developmental dyscalculia involve pattern recognition weakness? *Developmental Science, 16*, 35-46.

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,* S152-S166*.

Ashkenazi, S., Rubinsten, O., & Henik, A. (2009). Attention, automaticity, and developmental dyscalculia. *Neuropsychology, 23*, 535-540.

Barry, T. D., Lyman, R. D., & Klinger, L. G. (2002). Academic underachievement and attention deficit/hyperactivity disorder: The negative impact of symptom severity on school performance. *Journal of School Psychology, 40*, 259-283.

Benedetto-Nasho, E., & Tannock, R. (1999). Math computation, error patterns and stimulant effects in children with Attention Deficit Hyperactivity Disorder. *Journal of Attention Disorders, 3*, 121-134.

Biederman, J., Mick, E., Fried, R., Aleardi, M., Potter, A., & Herziq, K. (2005). A stimulated work place experience for non-medicated adults with and without ADHD. *Psychiatry Services, 56*, 1617-1620.

Biederman, J., Monuteaux, M. C., & Coyle, A. E. (2004). Impact of executive function deficits and attention-deficit hyperactivity disorder (ADHD) on academic outcomes in children. *Journal of Consulting and Clinical Psychology, 72*, 757-766.

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience, 16*, 1234-1249.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences, 8*, 539-546.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual–spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15*, 421–442.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46*, 3-18.

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences, 14*, 534-541.

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

Callejas, A., Lupiáñez, J., & Tudela, P. (2004). The three attentional networks: On their independence and interactions. *Brain and Cognition, 54*, 225-227.

Capano, L., Minden, D., Chen, S. X., Schachar, R. J., & Ickowicz, A. (2008). Mathematical learning disorder in school-age children with attention-deficit/hyperactivity disorder. *Canadian Journal of Psychiatry, 53*, 392-399.

Castellanos, F. X., Sonuga-Barke, E. J. S., Milham, M. P., & Tannock, R. (2006). Characterizing cognition in ADHD: beyond executive dysfunction. *Trends in Cognitive Sciences, 10*, 117-123.

Cattaneo, Z., Silvanto, J., Pascual-Leone, A., & Battelli, L. (2009). The role of the angular gyrus in the modulation of visuospatial attention by the mental number line. *NeuroImage, 15*, 563-568.

Cohen Kadosh, R., Cohen Kadosh, K., Schuhmann, T., Kaas, A., Goebel, R., Henik, A., & Sack, A. T. (2007). Virtual dyscalculia induced by parietal-lobe TMS impairs automatic magnitude processing. *Current Biology, 17*, 689-693.

Cohen Kadosh, R., Dowker, A., Heine, A., Kaufmann, L., & Kucian, K. (in press). Interventions for improving numerical abilities: Present and future. *Trends in Neuroscience and Education*.

Cohen Kadosh, R., Henik, A., Rubinsten, O., Mohr, H., Dori, H., van de Ven, V., . . . Linden, D. E. J. (2005). Are numbers special? The comparison systems of the human brain investigated by fMRI. *Neuropsychologia, 43*, 1238-1248.

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*, 132-147.

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology, 14*, 218-224.

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

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science, 284*, 970-974.

Derrfuss, J., Brass, M., Neumann, J., & von Cramon, D. Y. (2005). Involvement of the inferior frontal junction in cognitive control: Meta-analyses of switching and Stroop studies. *Human Brain Mapping, 25*, 22-34.

Dirks, E., Spyer, G., van Lieshout, E. C., & de Sonneville, L. (2008). Prevalence of combined reading and arithmetic disabilities. *Journal of Learning Disabilities, 41*, 460-473.

Estrada, C. A., Martin-Hryniewicz, M., Peek, B. T., Collins, C., & Byrd, J. C. (2004). Literacy and numeracy skills and anticoagulation control. *The American Journal of the Medical Sciences, 328*, 88-93.

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage, 26*, 471-479.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*, 340-347.

Geary, D. C. (1993). Mathematical disabilities: cognitive, neuropsychological, and genetic components. *Psychological Bulletin, 114*, 345-362.

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

Geary, D. C., Bow-Thomas, C. C., & Yao, Y. (1992). Counting knowledge and skill in cognitive addition: A comparison of normal and mathematically disabled children. *Journal of Experimental Child Psychology, 54*, 372-391.

Geary, D. C., & Hoard, M. K. (2001). Numerical and arithmetical deficits in learning-disabled children: Relation to dyscalculia and dyslexia. *Aphasiology, 15*, 635-647.

Geary, D. C., Hoard, M. K., & Hamson, C. O. (1999). Numerical and arithmetical cognition: Patterns of functions and deficits in children at risk for a mathematical disability. *Journal of Experimental Child Psychology, 74*, 213-239.

Ginsburg, H. P. (1997). Mathematics learning disabilities: a view from developmental psychology. *Journal of Learning Disabilities, 30*, 20-33.

Göbel, S., Walsh, V., & Rushworth, M. F. S. (2001). The mental number line and the human angular gyrus. *NeuroImage, 14*, 1278-1289.

Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., & Neuper, C. (2009). To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia, 47*, 604-608.

Grabner, R. H., Ischebeck, A., Reishofer, G., Koschutnig, K., Delazer, M., Ebner, F., & Neuper, C. (2009). Fact learning in complex arithmetic and figural-spatial tasks: The role of the angular gyrus and its relation to mathematical competence. *Human Brain Mapping, 30*, 2936-2952.

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

Henik, A., Rubinsten, O., & Ashkenazi, S. (2011). The 'where' and 'what' in developmental dyscalculia. *The Clinical Neuropsychologist, 25*, 989–1008.

Humphreys, C., Binder, J. R., Medler, D. A., & Liebenthal, E. (2007). Time course of semantic processes during sentence comprehension: An fMRI study. *NeuroImage, 3*, 924-932.

Ischebeck, A., Zamarian, L., Schocke, M., & Delazer, M. (2009). Flexible transfer of knowledge in mental arithmetic--an fMRI study. *NeuroImage, 44*, 1103-1112.

Jordan, N. C., Hanich, L. B., & Kaplan, D. (2003). A longitudinal study of mathematical competencies in children with specific mathematics difficulties versus children with co-morbid mathematics and reading difficulties. *Child Development, 74*, 834-850.

Jordan, N. C., Kaplan, D., & Hanich, L. B. (2002). Achievement growth in children with learning difficulties in mathematics: Findings of a two-year longitudinal study. *Journal of Educational Psychology, 94*, 586-597.

Kalanthroff, E., Goldfarb, L., Henik, A, (2013). Evidence for interaction between the stop-signal and the Stroop task conflict. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 579-592.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trend in Cognitive Science, 2*, 389-398.

Kaufmann, L., Koppelstaetter, F., Siedentopf, C., Haala, I., E., H., Zimmerhackl, L.-B., . . . Ischebeck, A. (2006). Neural correlates of the number-size interference task in children. *NeuroReport, 17*, 587-591.

Kaufmann, L., Lochy, A., Drexler, A., & Semenza, C. (2004). Deficient arithmetic fact retrieval—storage or access problem? A case study. *Neuropsychologia, 42*, 482–496.

Kaufmann, L., & Nuerk, H.-C. (2005). Numerical development: current issues and future perspectives. *Psychology Science, 47*, 142-170.

Kaufmann, L., & Nuerk, H.-C. (2008). Basic number processing deficits in ADHD: a broad examination of elementary and complex number processing skills in 9- to 12-year-old children with ADHD-C. *Developmental Science, 11*, 692-699.

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.

Kaufmann, L., Wood, G., Rubinsten, O., & Henik, A. (2011). Meta-analysis of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation. *Developmental Neuropsychology, 36*, 763-787.

Kucian, K., Kaufmann, L., & Von Aster, M. (in press). Brain Correlates of Numerical Disabilities. In R. Cohen Kadosh & A. Dowker (Eds.), *The Oxford Handbook of Numerical Cognition*: Oxford University Press.

Kucian, K., Leoenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: A functional MRI study. *Behavior and Brain Functions, 5*, 31.

Kucian, K., Loenneker, T., Martin, E., & von Aster, M. (2011). Non-Symbolic numerical distance effect in children with and without developmental dyscalculia: A parametric fMRI study. *Developmental Neuropsychology, 36*, 741-762.

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

Landerl, K., Fussenegger, B., Moll, K., & Willburger, E. (2009). Dyslexia and dyscalculia: two learning disorders with different cognitive profiles. *Journal of Experimental Child Psychology, 103*, 309-324.

Lee, K. M. (2000). Cortical areas differentially involved in multiplication and subtraction: a functional magnetic imaging study with a case of selective acalculia. *Annals of Neurology, 48*, 657-661.

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

Libertus, M. E., Waldorff, M. G., & Brannon, E. M. (2007). Electrophysiological evidence for notation intendance in numerical processing. *Behavioral and Brain Functions, 3*.

Lindsay, R., Tomazic, T., Levine, M., & Accardo, P. (2001). Attentional function as measured by a continuous performance task in children with dyscalculia. *Journal of Developmental and Behavioral Pediatrics, 22*, 287–292.

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

Mayes, S. D., Calhoun, S. L., & Crowell, E. W. (2000). Learning disabilities and ADHD: overlapping spectrum disorders. *Journal of Learning Disabilities, 33*, 417-424.

Moeller, K., Neuburger, S., Kaufmann, L., Landerl, K., & Nuerk, H.-C. (2009). Basic number processing deficits in developmental dyscalculia: evidence from eye-tracking. *Cognitive Development, 24*, 371-386.

Mussolin, C., De Volder, A., Grandin, C., Schlögel, X., Nassogne, M.-C., & Noël, M.-P. (2009). Neural correlates of symbolic number comparison in developmental dyscalculia. *Jounral of Cognitive Neuroscience, 22*, 860-874.

Mussolin, C., Mejias, S., & Noël, M.-P. (2010). Symbolic and nonsymbolic number comparison in children with and without dyscalculia. *Cognition, 115*, 10-25.

Noël, M.-P., & Rousselle, L. (2011). Developmental changes in the profiles of dscalculia: An explanation based on a double exact-and-approximate number representation model. *Frontiers in Human Neuroscience, 5*, 165.

Notebaert, K., Nelis, S., & Reynvoet, B. (2011). The magnitude representation of small and large symbolic numbers in the left and right hemisphere: an event-related fMRI study. *Journal of Cognitive Neuroscience, 23*, 622-630.

Parsons, S., & Bynner, J. (1997). Numeracy and employment. *Education + Training, 39*, 43-51.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron, 5*, 293-305.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*, 25-42.

Price, G. R., Holloway, I., Räsänen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology, 17*, 1042-1043.

Pugh, K. R., Mencl, W. E., Shaywitz, B. A., Shaywitz, S. E., Fulbright, R. K., Constable, R. T., . . . Gore, J. C. (2000). The angular gyrus in developmental dyslexia: task-specific differences in functional connectivity within posterior cortex. *Psychological Science, 11*, 51-56.

Rivera-Batiz, F. L. (1992). Quantitative literacy and the likelihood of employment among young adults in the United States. *Journal of Human Resources, 27*, 313-328.

Rosselli, M., Matute, E., Pinto, N., & Ardila, A. (2006). Memory abilities in children with subtypes of dyscalculia. *Developmental Neuropsychology*, *30*, 801-818.

Rotzer, S., Kucian, K., Martin, E., von Aster, M., Klaver, P., & Loenneker, T. (2008). Optimized voxel-based morphometry in children with developmental dyscalculia. *NeuroImage, 39*, 417-422.

Rotzer, S., Loenneker, T., Kucian, K., Martin, E., Klaver, P., & von Aster, M. (2009). Dysfunctional neural network of spatial working memory contributes to developmental dyscalculia. *Neuropsychologia, 47*, 2859–2865.

Rousselle, L., & Noël, M.-P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs non-symbolic number magnitude processing. *Cognition, 102*, 361-395.

Rubinsten, O. (2009). Co-occurrence of developmental disorders: The case of Developmental Dyscalculia. *Cognitive Development, 24*, 362-370.

Rubinsten, O., Bedard, A. C., & Tannock, R. (2008). Methylphenidate improves general but not core numerical abilities in ADHD children with co-morbid dyscalculia or mathematical difficulties. *Journal of Open Psychology, 1*, 11-17.

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. *Neuropsychology, 19*, 641-648.

Rubinsten, O., & Henik, A. (2006). Double dissociation of functions in developmental dyslexia and dyscalculia. *Journal of Educational Psychology, 98*, 854-867.

Rubinsten, O., & Henik, A. (2009). Developmental dyscalculia: Heterogeneity may not mean different mechanisms. *Trends in Cognitive Sciences, 13*, 92-99.

Rubinsten, O., & Henik, A. (2010). Comorbidity: Cognition and biology count! *Behavioral and Brain Sciences, 33*, 168-170.

Rusconi, E., Walsh, V., & Butterworth, B. (2005). Dexterity with numbers: rTMS over left anular gyrus disrupts finger anosis and number processing. *Neuropsychlogia, 43*, 1609-1624.

Russell, R. L., & Ginsburg, H. P. (1984). Cognitive analysis of children's mathematical difficulties. *Cognition and Instruction, 1*, 217-244.

Rykhlevskaia, E., Uddin, L. Q., Kondos, L., & Menon, V. (2009). Neuroanatomical correlates of developmental dyscalculia: combined evidence from morphometry and tractography. *Frontiers in Human Neuroscience, 3:51*. doi: 10.3389/neuro.09.051.2009

Schleifer, P., & Landerl, K. (2011). Subitizing and counting in typical and atypical development. *Developmental Science, 14*, 280-291.

Shalev, R. S. (2004). Developmental dyscalculia. *Journal of Child Neurology, 19*, 765-771.

Shalev, R. S., Auerbach, J., & Gross-Tsur, V. (1995). Developmental dyscalculia behavioral and attentional aspects: A research note. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 36*, 1261-1268.

Shalev, R. S., & Gross-Tsur, V. (2001). Developmental dyscalculia. *Pediatric Neurology, 24*, 337-342.

Simmons, F. R., & Singleton, C. (2008). Do weak phonological representations impact on arithmetic development? A review of research into arithmetic and dyslexia. *Dyslexia, 14*, 77-94.

Simon, O., Mangin, J.-F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. *Neuron, 33*, 475-487.

Skounti, M., Philalithis, A., & Galanakis, E. (2006). Variations in prevalence of attention deficit hyperactivity disorder worldwide. *European Journal of Pediatrics, 166*, 117-123.

Soltész, F., Szűcs, D., Dékány, J., Márkus, A., & Csépe, V. (2007). A combined event-related potential and neuropsychological investigation of developmental dyscalculia. *Neuroscience Letters, 417*, 181-186.

Song, J. H., & Jiang, Y. (2006). Visual working memory for simple and complex features: An fMRI study. *NeuroImage, 30*, 963-972.

Spira, E. G., & Fischel, J. E. (2005). The impact of preschool inattention, hyperactivity, and impulsivity on social and academic development: a review. *Journal of Child Psychology and Psychiatry, 46*, 755-773.

Szűcs, D., & Soltész, F. (2007). Event-related potentials dissociate facilitation and interference effects in the numerical Stroop paradigm. *Neuropsychologia, 45*, 3190-3202.

Tressoldi, P. E., Rosati, M., & Lucangeli, D. (2007). Patterns of developmental dyscalculia with or without dyslexia. *Neurocase, 13*, 217-225.

van Harskamp, N. J., Rudge, P., & Cipolotti, L. (2002). Are multiplication facts implemented by the left supramarginal and angular gyri? *Neuropsychologia, 40*, 1786-1793.

Venkatraman, V., Siong, S. C., & Chee, M. W., & Ansari, D. (2006). Effect of language switching on arithmetic: a bilingual fMRI study. *Journal of Cognitive Neuroscience, 18*, 64-74.

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences, 12*, 418-424.

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

Wu, S., Chang, T. T., Majid, A., Caspers, S., Eickhoff, S. B., & Menon, V. (2009). Functional heterogeneity of inferior parietal cortex during mathematical cognition assessed with cytoarchitectonic probability maps. *Cerebral Cortex, 19*, 2930-2945.

Zago, L., Petit, L. , Turbelin, M. R., F., A., Vigneau, M., & Tzourio-Mazoyer, N. (2008). How verbal and spatial manipulation networks contribute to calculation: An fMRI study. *Neuropsychologia, 46*, 2403-2414.

Zamarian, L., & Delazer, M. (in press). Arithmetic learning in adults – Evidence from brain imaging. In R. Cohen Kadosh & A. Dowker (Eds.), *The Oxford Handbook of Numerical Cognition*.

Zhou, X., Chen, C., Zang, Y., Dong, Q., Qiao, S., & Gong, Q. (2007). Dissociated brain organization for single-digit addition and multiplication. *NeuroImage, 35*, 871-880.