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Dissociation between exact and approximate addition in developmental dyslexia

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ABSTRACT

Previous research has suggested that number sense and language are involved in number representation and calculation, in which number sense supports approximate arithmetic, and language permits exact enumeration and calculation. Meanwhile, individuals with dyslexia have a core deficit in phonological processing. Based on these findings, we thus hypothesized that children with dyslexia may exhibit exact calculation impairment while doing mental arithmetic. The reaction time and accuracy while doing exact and approximate addition with symbolic Arabic digits and non-symbolic visual arrays of dots were compared between typically developing children and children with dyslexia. Reaction time analyses did not reveal any differences across two groups of children, the accuracies, interestingly, revealed a distinction of approximation and exact addition across two groups of children. Specifically, two groups of children had no differences in approximation. Children with dyslexia, however, had significantly lower accuracy in exact addition in both symbolic and non-symbolic tasks than that of typically developing children. Moreover, linguistic performances were selectively associated with exact calculation across individuals. These results suggested that children with dyslexia have a mental arithmetic deficit specifically in the realm of exact calculation, while their approximation ability is relatively intact.

1. Introduction

Developmental dyslexia, which affects 5%–10% of school-aged children (Snowling, 2000), is marked by unusually low reading achievement despite typical cognitive development. In past decades, studies have demonstrated that people with dyslexia have a core deficit of phonological processing (Bruck & Treiman, 1990; Fernandes, Vale, Martins, Morais, & Kolinsky, 2014; Swan & Goswami, 1997; Wagner & Torgesen, 1987). In addition, reading disorders are also characterized by pervasive deficits in spelling, rapid naming (Denckla & Rudel, 1976) and reading fluency (Poulsen & Elbro, 2013). Neuroimaging studies have also investigated the neural substrates of phonological processing deficits in people with dyslexia and have found that they have decreased gray matter density in the left inferior frontal gyrus and lower activation in the left superior temporal sulcus compared to controls (Eckert, 2004; Richlan, Kronbichler, & Wimmer, 2013; Boets et al., 2013). For logographic Chinese, the frequently reported deficits in dyslexic readers are orthographic processing, phonological processing, morphological

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awareness, and rapid naming (McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003; Ho, Chan, Lee, Tsang, & Luan, 2004; Siok & Fletcher, 2001).

Interestingly, neuropsychological studies have indicated an overlap of brain activation between reading and calculation. For example, the left angular gyrus is activated during both reading and arithmetic operations (Meyler et al., 2007), which suggests that there might be a connection between reading and arithmetic processing. Indeed, strong correlations have been found between calculating performance and that of vocabulary, reading fluency and rapid automatized naming (Koponen, Salmi, Eklund, & Aro, 2013; Stanescu-Cosson et al., 2000). Additionally, reading disorders often coexist with difficulties in mathematics in spite of normal intellectual ability (Landerl & Moll, 2010; Ramus et al., 2003; Light & Defries, 1995). Further studies have identified verbal/phonological processing as one of the cognitive mechanisms underlying this connection and coexistence (Hecht, Torgesen, Wagner, & Rashotte, 2001; De Smedt & Boets, 2010; De Smedt, Taylor, Archibald, & Ansari, 2010).

However, the studies abovementioned investigating the connection of reading development and arithmetic skills and/or coexistence of reading impairment and arithmetic disability primarily used a calculation task, with, for example, multiplication, addition or subtraction, which mainly tapped arithmetic using exact calculation (De Smedt, Taylor, Archibald, & Ansari, 2010; Simmons, Singleton, & Horne, 2008). In fact, a wealth of literature has recently suggested that number representations involve two distinct systems: the language-dependent exact calculation system (Dehaene & Cohen, 1997; Lemer, Dehaene, Spelke, & Cohen, 2003; Pica, Lemer, Izard, & Dehaene, 2004) and the nonverbal number sense system supported approximate representation system (Pica, Lemer, Izard, & Dehaene, 2004; Piffer, Agrillo, & Hyde, 2012; Tomonaga, 2008; Xu & Spelke, 2000). Specifically, research suggests that the exact numerical representations and operations beyond number three or four are supported by the language-based exact calculation system, while subitizing exact number under three or four and discrimination of quantities larger than three approximately are estimated by the number sense system which supports a primitive sense of numbers in infants, children, adults, and even animals (Antell & Keating, 1983; Hauser, Carey, & Hauser, 2000). The strong relationship between exact calculation and language is evidenced by the phonological length effect (Barrouillet & Thevenot, 2013; Zbrodoff & Logan, 2005), the inability of exact calculation observed in primitive tribes (Gordon, 2004), in severely aphasic patients (Dehaene and Cohen, 1991), and in patients with semantic dementia (Lemer, Dehaene, Spelke, & Cohen, 2003). Additionally, investigations with young children (Gilmore, McCarthy, & Spelke, 2007; Lemer et al., 2003; Spelke & Tsivkin, 2001) also claimed a distinction of approximation and exact arithmetic. Notably, the dissociation between exact calculation and approximation is strengthened by the different brain activations during exact calculation and approximation. That is, greater activation during approximation was observed in the visuo-spatial networks of the bilateral inferior parietal lobule. Conversely, the left inferior prefrontal cortex and the left angular gyrus showed greater activation during exact calculation than during approximation (Daheane, Spelke, Pinel, Stanescu, & Tsivkin, 1999).

Although numerous studies have shown a strong relation between language ability and mathematical ability, how language processing is involved in mathematical performance remains unclear. The primary purpose of the present study was to explore how language affects arithmetic by investigating whether there are differential effects of language on two common arithmetic tasks of exact and approximate addition in Chinese-speaking children with and without dyslexia. Considering that a phonological processing deficit was the core deficit in dyslexia and verbal/phonological processing was mainly involved in exact calculation, we predicted that typically developing children should outperform children with dyslexia in exact addition, but not in approximation.

The triple-code model assumes numbers are mentally manipulated in an Arabic, verbal or analogical magnitude code (Dehaene, 1992; Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). The present study was, accordingly, designed to clarify whether the above hypotheses are compatible with different mental codes, the symbolic Arabic, and the non-symbolic arrays of dots. Specifically, experiment 1 was conducted with the symbolic Arabic digits, while experiment 2 was carried out with a non-symbolic task presented with arrays of dots.

Prior work suggest that plausible distinctions exist between small and large number calculations (Trick & Pylyshyn, 1994; Mandler & Shebo, 1982; Cohen & Dehaene, 1994). That is, small numbers/quantities under 3, or 4 can be precisely distinguished through subitizing in non-symbolic calculation. However, the exact operations of small numbers with symbolic Arabic digits are achieved through fact retrieval due to daily rote learning (Dehaene & Cohen, 1995; Geary, 2000), so the small number exact calculation in symbolic addition and the exact numerations above three or four in both symbolic and non-symbolic calculations are supposed to involve language/verbal processing. Therefore, we involved two types of addends in our experiments. In the symbolic addition task, for the small number addition task, operands ranged from 1 to 5, and for the large number addition task, operands ranged from 5 to 9 (Stanescu-Cosson et al., 2000). Analogously in non-symbolic addition, we also involved two types of addends with dot arrays, more than three and less than three. As subitizing is evolutionarily innate and unrelated to language processing (Feigenson, Dehaene, & Spelke, 2004), we predicted that children with dyslexia would have compatible performance to that of controls in small number addition with non-symbolic arrays of dots regardless of exact or approximate addition. For exact addition with a larger number array of dots and exact addition with symbolic digits, children with dyslexia, however, should have poorer performance than that of controls because exact calculation with small digital calculation involves fact retrieval and larger number calculation with both symbolic and non-symbolic stimuli would incorporate phonological processing.

Additionally, given previous studies showed that arithmetic was strongly associated with verbal/phonological processing abilities (De Smedt et al., 2010), in order to further explore the mechanisms of the distinction, if any, in performance of exact and approximate addition in dyslexia and non-dyslexia, verbal/phonological processing skills were evaluated with a