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Symbolic and non-symbolic number processing in children with developmental dyslexia

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ABSTRACT

This study examined number processing in 10-year-olds with developmental dyslexia (DD). The phonological deficit and double deficit hypotheses imply that children with DD might have a connection deficit that affects their ability to establish links between number symbols and magnitude representations. The double deficit hypothesis also posits that symbolic number difficulties may emerge due to difficulties with processes underlying rapid automatic naming (RAN). The DD group displayed difficulties with symbolic number processing but not with non-symbolic number processing. However, the underlying processes of this access or connection deficit appeared not to be related to phonological awareness or RAN. The DD group displayed impaired arithmetic fluency and calculation that were accounted for by defective processes underlying RAN. In view of the triple-code model, children with DD have impaired verbal number codes or defective access to verbal number codes but an intact core magnitude representation.

1. Introduction

Developmental dyslexia (DD) refers to a specific learning disorder characterized by a persistent deficit in accurate and/or fluent word recognition and/or by poor spelling (American Psychiatric Association, 2013). There are several hypotheses concerning the causes of DD. Defective phonological representations are considered to be one of the core problems of DD (e.g., Peterson & Pennington, 2012; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Ramus & Ahissar, 2012). The indistinct phonological representations of individuals with DD hamper their ability to establish links between graphemes and phonemes. This grapheme–phoneme correspondence is a vital process to learn to read an alphabetic written language system (Ramus et al, 2003; Snowling, 2000).

Another account of DD is the double deficit hypothesis (Wolf & Bowers, 1999) stating that DD is due to two independent deficits: indistinct phonological representations and/or impairment in processes underlying rapid automatic naming (RAN; Torppa, Georgiou, Salmi, Eklund, & Lyytinen, 2012). The double deficit hypothesis distinguishes three deficit subtypes, phonological deficit, and RAN deficit, and double deficit (combination of the two single core deficit subtypes) (Steacy, Kirby, Parrila, & Compton, 2014; Wolf, Bowers, & Biddle, 2000). People with the phonological deficit subtype have problems with phonological awareness, word decoding, and reading comprehension, but not with RAN. Those with the RAN deficit subtype have problems with RAN, verbal fluency, reading comprehension and reading under timed conditions but not with phonological awareness and word decoding. Those with the double deficit subtype have problem with all the aforementioned areas (Steacy et al., 2014; Torppa et al., 2013).

Similar to reading, learning mathematics requires learning the language-based symbolic number system (e.g., number words; numerals) and connecting it to the innate non-symbolic number system (Butterworth, 2010; Dehaene, 1992; Geary, 2004; von Aster & Shalev, 2007). Children begin to acquire the language-based symbolic number system when learning to talk (Gelman & Butterworth, 2005; Piazza, 2010; von Aster & Shalev, 2007). It is assumed that children first learn the counting words by rote and connect them to the innate number system. Then they learn the Arabic numerals and connect them to the counting words and the innate number system (Carey, 2004; Dehaene, 2011; Geary, 2013; Le Corre & Carey, 2007; von Aster & Shalev, 2007). Empirical support of the assumption that children's learning of the symbolic number system depends on language skills has been provided by LeFevre et al. (2010); see also Krajewski & Schneider, 2009). According to the Triple code model (Dehaene, 1992; see also von Aster & Shalev, 2007)), children possess three interconnected number codes: 1) the innate analogue number representation used for number comparison, number estimation and approximate arithmetic, 2) a verbal number code used for counting, and establishing

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and retrieving arithmetic facts and 3) a visual Arabic number code used during written multi-digit calculation.

Theoretically inspired by the Triple-code model, an increasing number of researchers have examined mathematical skills in dyslexia (Simmons & Singleton, 2008). This research provides evidence that individuals with dyslexia have difficulties with specific aspects of mathematics. Consistent with the Triple-code model, stating that arithmetic facts are represented via a phonological code, individuals with dyslexia display impaired arithmetic fact retrieval and/or fluency skills, presumably due to their indistinct phonological representations (De Smedt & Boets, 2010; Göbel & Snowling, 2010; Simmons & Singleton, 2008; Träff & Passolunghi, 2015; Vukovic, Lesaux, & Siegel, 2010). In contrast, they show no evidence of weakness concerning approximate symbolic arithmetic assumed to rely on the innate analogue magnitude representation and visual Arabic number code (Göbel & Snowling, 2010; Hanich, Jordan, Kaplan, & Dick, 2001). However, a few studies suggest that children with dyslexia also have problems with written multi-digit calculation, which is assumed to rely on the visual Arabic number code (Jordan, Hanich, & Kaplan, 2003; Träff & Passolunghi, 2015; Vukovic et al., 2010). This unexpected weakness is probably due to that efficient multi-digit calculation requires fast and accurate retrieval of number facts, which depend on a verbal-phonological code (Andersson, 2008; Ashcraft, 1992, 1995; McCloskey, Caramazza, & Basili, 1985; Träff, 2013; Träff & Passolunghi, 2015).

The present study sought out to further expand our knowledge with respect to mathematical skills in dyslexia by examining if children with dyslexia displaying difficulties with number processing.

To date, few studies have examined number processing in individuals with DD. Göbel and Snowling (2010) examined symbolic number processing in adults with DD. They found that adults with DD performed symbolic number comparison as accurate and fast as the controls. The size of the numerical distance effect was also similar to the controls. In the De Smedt and Boets (2010) study, adults with dyslexia performed non-symbolic number comparison equal to the controls. These two studies suggest that adults with DD appear to have intact number processing skills. However, two recent studies indicate that children with DD have difficulties with symbolic (verbal, Arabic) number processing, but not non-symbolic number processing (Moll, Göbel, & Snowling, 2015; Raddatz, Kuhn, Holling, Moll, & Dobel, 2016). In Moll et al. (2015) children with DD displayed difficulties with verbal counting, dot-counting (5–7 dots range), identifying and transcoding orally presented one-digit and multi-digit numbers, and symbolic number comparison. The children in Raddatz et al. (2016) performed poorly in dot-counting (5–9 dots range), and transcoding orally presented numbers, but not in symbolic number comparison.

A feasible account of the contradictory findings concerning number processing in children with DD and adults with DD is that children have had less time and experience with the symbolic number system compared with adults. They might not have established efficient and automatized links between the number symbols and underlying magnitudes. In view of the phonological deficit hypothesis and the double deficit hypothesis, it is plausible that the defective grapheme–phoneme correspondence that characterizes children with dyslexia also affect their ability to connect the language-based symbolic number system, especially counting words, with the underlying analogue magnitude representation. Thus, both hypotheses predict that children with dyslexia should display difficulties with symbolic number comparison due to their indistinct phonological representations but not with non-symbolic number comparison because their magnitude representation is assumed to be intact. Moreover, they should display normal distance and problem size effects when performing symbolic number comparison as their magnitude representation is assumed to be unaffected. Indeed, an account of developmental dyscalculia, *the access deficit hypothesis* (Rousselle & Noël, 2007), states that dyscalculia is caused by a defective connection between the symbols (e.g., counting words; digits) and the underlying magnitude representation (see also Wilson & Dehaene, 2007).

The double deficit hypothesis also states that children with DD should have difficulties with processes underlying RAN, that is, the speed with which an individual names a series of highly familiar visual stimuli (Wolf et al., 2000). This seemingly simple task entails a number of processes such as attention; visual pattern identification; integration of visual information with stored orthographic and phonological representations; access and retrieval of phonological codes; and organization of articulatory output (see Norton & Wolf, 2012 for a review). The question is whether a RAN deficit has any negative effects on the performance of basic mathematical tasks. In some studies, RAN has been found to predict arithmetic fluency (e.g., Koponen, Salmi, Eklund, & Aro, 2013; Koponen et al., 2016) whereas other studies have failed to obtain such a connection (Heikkilä, Torppa, Aro, Närhi, & Ahonen, 2016). Theoretically, a RAN deficit may hamper performance on all tasks involving speeded retrieval of information from visual numerical symbols (i.e., digits), even though no verbal response is required. If so, it predicts that children with DD should display difficulties with many of the mathematical tasks included in the study, especially symbolic number comparison.

As prior research shows that children with dyslexia have difficulties with specific aspects of mathematics, the present study included tasks tapping arithmetic fluency, calculation, and approximate arithmetic. The study also included tasks tapping phonological awareness, RAN, general processing speed, verbal working memory, and visual-spatial working memory. These tasks were selected because research shows that individuals with dyslexia are impaired on these functions (De Weerdt, Desoete, & Roeyers, 2013a, 2013b; Fletcher et al., 1994; Helland & Asbjørnsen, 2000; Menghinia et al., 2010; Reiter, Reiter, Tucha, & Lange, 2005; Stanovich & Siegel, 1994; Stein & Walsh, 1997) or/and that they contribute to mathematical performance and development (e.g., Andersson, 2007; Berg, 2008; Bull, Espy, & Wiebe, 2008; Geary, 2004; Passolunghi, Mammarella, & Altoè, 2008; Passolunghi & Pazzaglia, 2004; Swanson, 1994; Träff, 2013).

2. Material and methods

2.1. Participants

In total, 20 fourth-graders with DD and 35 age-matched fourth-graders without learning disabilities participated in the study. They were recruited by means of a letter of consent that the children took home to the parents from school. All children were fluent speakers of Swedish, had normal or corrected-to-normal visual acuity, and no hearing loss. The selection of the 20 children with dyslexia was based on four criteria to comply with the definition of DD in DSM 5, that is, a severe, persistent, and specific learning disorder (American Psychiatric Association, 2013). First, the child should have received individually adapted special education instructions in reading and writing (i.e., Swedish) during the last year and at the time of the study but should never have received any special education instruction in any other subject. (cf. Andersson & Östergren, 2012; Skagerlund & Träff, 2016). Second, in grade three, the child should have passed the national assessment tests in mathematics administered by the Swedish National Agency for Education. The first and second criteria were important in order to exclude the possibility that some of the children with dyslexia also were low achievers in mathematics. Third, the child should not have had any neuropsychological disturbances (e.g., ADHD). Fourth, the child's score on a standardized word-decoding task (see below) had to be at or below the 10th percentile of the test norms. The 35 children in the control group had to have word-decoding scores between the 15th and the 85th percentile and should never have received any special education instruction.

In addition to the word-decoding task, a text-reading task and a measure of fluid intelligence (Raven, 1976) were administered. Information regarding background variables and results on the reading tests and the Raven's test are presented in Table 1. The number of girls