Neuropsychologia 48 (2010) 3973–3981

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Phonological processing and arithmetic fact retrieval: Evidence from developmental dyslexia

Bert De Smedt[*,1], Bart Boets[1]

Centre for Parenting, Child Welfare & Disabilities, Faculty of Psychology and Educational Sciences, Katholieke Universiteit Leuven, Belgium

ARTICLE INFO

Article history:
Received 9 December 2009
Received in revised form 11 October 2010
Accepted 12 October 2010
Available online 20 October 2010

Keywords:
Dyslexia
Fact retrieval
Arithmetic
Phonological processing
Angular gyrus

ABSTRACT

The triple-code model, cognitive neuroimaging and developmental behavioral data suggest a specific association between phonological processing and arithmetic fact retrieval. Accordingly, individuals with deficits in phonological processing, such as individuals with developmental dyslexia, are expected to show difficulties in arithmetic fact retrieval. The present study tested this proposal in 25 adults with developmental dyslexia and 25 matched controls by examining strategy use during single-digit multiplication and subtraction and its associations with phonological processing. Findings revealed that individuals with dyslexia retrieved fewer arithmetic facts from memory and were less efficient in doing so. At the same time, they showed deficits in phonological processing. Phonological processing, particularly phonological awareness, was related to arithmetic fact retrieval. This association was especially prominent in multiplication, indicating that fact retrieval in multiplication rather than subtraction is mediated by phonological processes. These data provide ground for future neuroimaging studies, who should examine the neural overlap between phonological processing and multiplication fact retrieval in the same sample of participants.

1. Introduction

There are several reasons for suggesting a specific relation between phonological processing and arithmetic fact retrieval. The triple-code model postulates that numerals can be represented in a verbal-phonological code, which is used in verbally mediated arithmetic tasks such as retrieving arithmetic facts from memory, particularly in multiplication (Dehaene, 1992; Dehaene & Cohen, 1995; Dehaene, Piazza, Pinel, & Cohen, 2003). Cognitive neuroimaging data suggest a neural overlap between phonological processing and arithmetic fact retrieval in the left-temporo-parietal junction, in particular in the left angular and supramarginal gyri (Dehaene et al., 2003; Grabner et al., 2009; Pugh et al., 2001; Schlaggar & Mccandliss, 2007; Vigneau et al., 2006). Recent developmental research shows a specific relation between phonological awareness and arithmetic fact retrieval (De Smedt, Taylor, Archibald, & Ansari, 2010). If a reliable relation between phonological processing and arithmetic fact retrieval exists, then individuals with deficits in phonological processing, such as individuals with developmental dyslexia (e.g., Ramus et al., 2003; Snowling, 2000; Vellutino, Fletcher, Snowling, & Scanlon, 2004), are expected to show difficulties with arithmetic fact retrieval. Although such a relation has been postulated theoretically (Dehaene et al., 2003; Simmons & Singleton, 2008), there are, to our knowledge, no empirical studies that have investigated this association systematically. The present study therefore aimed to examine this association in adults with developmental dyslexia, a neurodevelopmental disorder in learning to read and to write despite normal IQ and adequate instruction. Such data might further shed light on the general associations between phonological processing and arithmetic fact retrieval and their underlying neural correlates.

1.1. Arithmetic in dyslexia

Several studies have indicated that multiplication is difficult for children with dyslexia (Miles, 1983; Simmons & Singleton, 2008; Turner Ellis, Miles, & Wheeler, 1996), although these studies did not systematically examine other operations or the strategies that children apply during problem solving. Landerl, Bevan, and Butterworth (2004) investigated single-digit arithmetic in children with dyscalculia, children with dyslexia and children with comorbid dyscalculia and dyslexia. These authors did not find significant group differences between children with dyslexia without dyscalculia and controls on single-digit addition, subtraction and multiplication. However, a careful inspection of their reaction time

* Corresponding author at: Centre for Parenting, Child Welfare & Disabilities, Katholieke Universiteit Leuven, Vesaliusstraat 2, Box 3765, Leuven, Belgium. Tel.: +32 16 32 57 05; fax: +32 16 32 59 33.
E-mail addresses: Bert.DeSmedt@ped.kuleuven.be, bert.desmedt@ped.kuleuven.ac.be (B. De Smedt).
[1] Both authors equally contributed to this study and should be regarded as joint first authors.

0028-3932/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.neuropsychologia.2010.10.018

data suggests that children with dyslexia were slower than controls in multiplication and addition, but not in subtraction. It is also unclear whether the children identified as dyslexic in this study had phonological impairments. Thus, the precise arithmetical difficulties of children with dyslexia remain to be determined.

Studies on arithmetic in adults with developmental dyslexia are scarce. Temple (1991) reported a 19-year-old female patient with developmental phonological dyslexia, without manifest neurological impairment, who showed a specific deficit in multiplication. This patient had no other difficulties in calculation and her number processing skills were normal.

Simmons and Singleton (2006) provided the first systematic investigation of different single-digit arithmetic operations, comprising addition, subtraction and multiplication, in university students with developmental dyslexia. They showed that these students were less accurate in subtraction and multiplication. Students with dyslexia were slower in addition and subtraction, but there was only a trend for group differences in multiplication. More recently, Göbel and Snowling (2010) demonstrated that adults with developmental dyslexia, who had normal number processing skills, were significantly slower than controls in single-digit addition and multiplication. No group differences in accuracy were observed, which contrasts with earlier findings by Simmons and Singleton (2006).

Against the background of their data, Simmons and Singleton (2006) and Göbel and Snowling (2010) concluded that individuals with dyslexia have difficulties in arithmetic fact retrieval. This conclusion should be interpreted with caution as the authors did not assess the strategies that participants applied during problem solving. Indeed, studies that collected verbal protocol data to examine single-digit arithmetic strategy use reported that adults use a variety of strategies (e.g., Campbell & Xue, 2001; Grabner et al., 2009; Lefevre, Sadesky, & Bisanz, 1996). Although adults may often retrieve the answer to a problem directly from memory, other strategies are also applied; for example, calculation of the answer by means of a procedure or by counting, both of which are more time-consuming and rely stronger on magnitude processing and working memory. Grabner et al. (2009) demonstrated that verbal reports of different strategies correlated with activity in different brain regions: retrieval use was related to activation in the left angular gyrus whereas procedure use engaged a wider fronto-parietal network. For the hypothesis of fact retrieval difficulties in dyslexia to be supported, it needs to be demonstrated that individuals with developmental dyslexia either report fewer fact retrieval use or that they perform less accurately or more slowly when retrieving arithmetic facts from memory. To date, no such strategy data exist.

1.2. Arithmetic fact retrieval and phonological processing

Simmons and Singleton (2008) suggested that the poor arithmetic fact retrieval in dyslexia might be explained by their weak phonological processing skills. An association between phonological processing and arithmetic has been observed in typically developing children (De Smedt et al., 2010; Fuchs et al., 2005; Hecht, Torgesen, Wagner, & Rashotte, 2001). More specifically, De Smedt et al. (2010) showed that in third graders fact retrieval was uniquely associated with phonological awareness but not with phonological memory. These authors suggested that the quality of phonological representations may be a key factor for efficient fact retrieval in a way that more distinct phonological representations contribute to a more efficient, i.e., faster and more accurate, retrieval of arithmetic facts. Few studies have addressed this association between phonological processing and fact retrieval in healthy adults. For example, Lee and Kang (2002) revealed in a dual-task experiment that phonological memory load impaired performance in single-digit multiplication but not in subtraction. Others, however, failed to find an effect of phonological memory load on single-digit multiplication performance (De Rammelaere, Stuyven, & Vandierendonck, 1999; Seitz & Schumann Hengsteler, 2000). Similarly, Simmons and Singleton found no association between verbal short-term memory and arithmetic fact retrieval in dyslexia, but it should be noted that their sample size was very small. Taken together, behavioral findings on the association between phonological processing and arithmetic fact retrieval remain inconclusive.

Cognitive neuroimaging data might further shed light on this issue. Neuroimaging studies of arithmetic have revealed that particularly the left angular gyrus is engaged during arithmetic problem types that are solved by means of fact retrieval (Grabner et al., 2007; Grabner et al., 2009). It appears that these left temporo-parietal areas are also activated during phonological decoding and during tasks that involve effortful phonological analysis (Gelfand & Bookheimer, 2003; Pugh et al., 2001; Shaywitz et al., 1998), suggesting that those tasks that put the highest demands on phonological representations are expected to reveal the strongest associations with arithmetic fact retrieval. Furthermore, individuals with dyslexia show less activation in the left temporo-parietal junction during tasks that involve effortful phonological analysis (McCandliss & Noble, 2003; Pugh et al., 2001; Shaywitz et al., 1998; Temple, 2002). Against this background, it can be hypothesized that the arithmetic fact retrieval difficulties in dyslexia are due to their phonological processing deficits.

1.3. The present study

The present study aimed to examine arithmetic fact retrieval and its relation with phonological processing in adults with developmental dyslexia and matched controls. We collected strategy assessments during single-digit multiplication and subtraction to directly test whether adults with developmental dyslexia have difficulties in retrieving arithmetic facts. We further investigated whether these fact retrieval difficulties could be explained by individual differences in the three classic areas of phonological processing, i.e., phonological awareness, lexical access to long-term memory, and verbal short-term memory (Wagner & Torgesen, 1987).

We expected that participants with dyslexia would retrieve fewer arithmetic facts from memory than controls. We also hypothesized that participants with dyslexia would show poor performance on the administered phonological measures and we expected associations between phonological processing and arithmetic fact retrieval use. Because fact retrieval is more often used in multiplication than in subtraction (e.g., Campbell & Xue, 2001) and because multiplication shows increased activation in the left angular gyrus compared to subtraction, suggesting that it relies more on a verbal code than subtraction (Chochon, Cohen, Van De Moortele, & Dehaene, 1999; Dehaene et al., 2003; Lee, 2000), we expected that group differences in arithmetic would be most prominent in multiplication and we predicted that associations between phonological processing and arithmetic would be stronger for multiplication than for subtraction.

It is important to note that difficulties in arithmetic fact retrieval may be due to a deficit in representing numerical magnitudes, as is the case in developmental dyscalculia (Butterworth, 2005; Landerl et al., 2004; Wilson & Dehaene, 2007). Individuals with this neurodevelopmental disorder have a core deficit in understanding and manipulating numerical magnitudes, due to abnormalities in the intraparietal sulcus, which lead to general deficits in arithmetic (Butterworth, 2005; Landerl et al., 2004; Wilson & Dehaene, 2007). Most important, developmental dyscalculia and developmental dyslexia are known to co-occur frequently (e.g., Shalev, 2007). The arithmetic difficulties of this comorbid subgroup of individuals with developmental dyslexia might be explained by their impaired