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Early language and executive skills predict variations in number and arithmetic skills in children at family-risk of dyslexia and typically developing controls

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ABSTRACT

Two important foundations for learning are language and executive skills. Data from a longitudinal study tracking the development of 93 children at family-risk of dyslexia and 76 controls was used to investigate the influence of these skills on the development of arithmetic. A two-group longitudinal path model assessed the relationships between language and executive skills at 3–4 years, verbal number skills (counting and number knowledge) and phonological processing skills at 4–5 years, and written arithmetic in primary school.

The same cognitive processes accounted for variability in arithmetic skills in both groups. Early language and executive skills predicted variations in preschool verbal number skills, which in turn, predicted arithmetic skills in school. In contrast, phonological awareness was not a predictor of later arithmetic skills. These results suggest that verbal and executive processes provide the foundation for verbal number skills, which in turn influence the development of formal arithmetic skills. Problems in early language development may explain the comorbidity between reading and mathematics disorder.

1. Introduction

Reading and mathematics disorder frequently co-occur, but so far we lack an understanding of the cognitive mechanisms that account for this comorbidity. In this paper we explore possible explanations by examining early language and executive skills in children at family-risk of dyslexia. Understanding the influences on arithmetic development in children with and without reading difficulties is important for understanding the development of, and comorbidities between, language, reading and arithmetic problems. This study focuses on the role of early language skills and domain-general skills of nonverbal IQ and executive skills as foundations for the development of arithmetic skills and the mediating role of the exact verbal number system in typically developing children and children at risk of dyslexia. More specifically, we explore the extent to which nonverbal IQ, language and executive skills may constrain children's ability to learn to count and to learn number names before the onset of formal teaching. We then relate variations in these domain-specific verbal number skills (counting and number knowledge) to measures of formal arithmetic ability assessed some two years after the onset of formal schooling.

It has often been argued that magnitude processing skills provide the cognitive foundations for the development of arithmetic. Two *pre-verbal core systems* for representing numerosities have been distinguished. The first is an approximate number system (ANS; Dehaene, 1992) which represents magnitudes in an *approximate* way. The second system, the object tracking system (OTS), represents small numbers of objects in an *exact* way (Piazza, 2010). These pre-verbal systems have been considered to be innate (Feigenson, Dehaene, & Spelke, 2004), and to provide the initial basis for representing numerosities and their meaning *before* language is acquired (von Aster & Shalev, 2007). During the preschool and early school years spoken number–words and Arabic digits are

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taught and these verbal-symbolic representations acquire their meaning by being mapped onto the preverbal core systems.

According to von Aster and Shalev (2007) the acquisition of the verbal-symbolic number system not only builds on the preverbal core systems but also depends on language and domain-general skills. For example, if language or executive skills are deficient, then verbal number skills (e.g., counting) might not develop normally and associations between verbal-symbolic representations and non-symbolic representations would suffer. Consequently, children with language or reading problems are at risk of developing arithmetic difficulties.

Indeed, previous studies have found that individuals with language or reading problems perform poorly on arithmetic tasks (e.g., fact retrieval) compared to individuals without language or reading problems (De Smedt & Boets, 2010; Göbel & Snowling, 2010; Miles, Haslam, & Wheeler, 2001; Simmons & Singleton, 2006). Furthermore, individuals with reading disorder are impaired in verbal number tasks, such as counting, but seem to be unimpaired on nonverbal tasks tapping the ANS (e.g., Göbel & Snowling, 2010; Moll, Göbel, & Snowling, 2014). It has been argued, that problems in fact retrieval in children with dyslexia are mediated by their reading problems (Mammarella et al., 2013). Thus, poor arithmetic skills in children with reading disorder are associated with problems in language processing, rather than with problems in basic number processing. In contrast, children with dyscalculia seem to be impaired in a wider range of number skills and their poor arithmetic skills are associated with problems in basic number processing (Moll et al., 2014). Consistent with this, the core deficits underlying reading disorder are distinct from those underlying mathematics disorder (Ashkenazi, Black, Abrams, Hoeft, & Menon, 2013; Landerl, Fussenegger, Moll, & Willburger, 2009), with a phonological deficit being one proximal cause of reading difficulties (Vellutino, Fletcher, Snowling, & Scanlon, 2004) and a deficit in processing numerosities being associated with mathematics difficulties (Butterworth, 2010; Wilson & Dehaene, 2007). It follows that early language problems and non-verbal number deficits may constitute separable risk factors for arithmetic disorder. Children with poor language skills may therefore be at risk of developing arithmetic difficulties in spite of the fact that their non-verbal number skills are unaffected.

In order to trace possible causal influences from early cognitive skills to later arithmetic attainment, longitudinal studies starting before children enter formal education are required. Remarkably few such studies have been published to date. One of the few studies (LeFevre et al., 2010) followed children from the age of 4½ to 7½ years. At the beginning of the study, language measures (vocabulary and phoneme deletion) predicted concurrent variations in children's number naming, whereas a measure of quantitative knowledge, namely subitizing (immediate apprehension of small quantities, as measured by the time used to indicate the number of dots in an array of 1–3 dots), predicted concurrent variations in a nonverbal arithmetic task. Variations in a “linguistic” factor (vocabulary, phoneme awareness and number naming) and a “quantitative” factor (subitizing and nonverbal arithmetic) were both predictors of conventional arithmetic skills assessed when children were 7½ years old, with effects from the “linguistic” factor being stronger. These findings suggest that variations in children's early language skills (broadly defined) provide a foundation for the development of arithmetic skills once formal teaching begins. The role of language skills in the development of mathematical abilities is further supported by studies showing that children with language impairment perform poorly on arithmetic compared to typically developing controls (Donlan, Cowan, Newton, & Lloyd, 2007; Fazio, 1996; Koponen, Mononen, Rasanen, & Ahonen, 2006).

In addition to the role of language skills, studies analyzing the impact of domain-general skills on arithmetic have reported associations between aspects of executive functioning, but not nonverbal IQ, and children's mathematical skills (e.g., Bull, Espy, & Wiebe, 2008; Bull & Scerif, 2001; Espy et al., 2004; van der Sluis, de Jong, & van der Leij, 2004). However, the importance of nonverbal IQ may increase across grades (Geary, 2011) when the demands of arithmetic tasks increase (e.g., written calculations with two-digit numbers) and when tasks involve problem solving (Hembree, 1992; Vickers, Mayo, Heitmann, Lee, & Hughes, 2004; Xin & Zhang, 2009). In line with this, Kyttälä and Lehto (2008) reported that nonverbal IQ predicted individual differences in complex mental arithmetic tasks and written word problems (including percentage calculations and equations) in 15–16 year olds (see also Deary, Strand, Smith, & Fernandes, 2007). Nonverbal IQ is also strongly related to nonverbal number tasks (e.g., relations between quantities, number line estimation). For example, Hornung, Schiltz, Brunner, and Martin (2014) recently reported a strong and direct association between nonverbal IQ (assessed at the end of kindergarten) and performance in a number line estimation task assessed one year later; this association was not mediated by preschool number skills.

Turning to executive functioning, comparatively little is known about the development of executive functions in the preschool years and their relationship to later academic skills and studies assessing executive functions in children as young as 3–4 years are very rare (see Garon, Bryson, & Smith, 2008). In the influential framework of Miyake et al. (2000) executive functions form a unitary construct, but with partly dissociable components: (1) *working memory/updating* (holding, manipulating and updating information in mind) (2) *inhibition* (the ability to suppress irrelevant or distracting information and prevent predominant responses), and (3) *set shifting* (the flexibility to switch between different tasks).

The relationship between executive functioning and the development of mathematical skills was recently summarized in a review by Cragg and Gilmore (2014). For *working memory* it has been suggested that the ability to manipulate and update information may be particularly crucial for developing mathematical skills. Such an ability is required when solving word problems as well as when calculating two-digit additions involving carrying (e.g., 15 + 17). It has been suggested that the role of verbal working memory increases with age, when the problems being solved become more complex (Geary, 2011; McKenzie, Bull, & Gray, 2003; von Aster & Shalev, 2007). *Inhibition* has been linked to performance in tasks including inversion shortcuts in addition and subtraction (Robinson & Dubé, 2013) as well as in counting tasks when counting on from the larger addend instead of counting on from the first addend (e.g. Cragg & Gilmore, 2014) and in multiplication tasks when suppressing answers to related but incorrect number facts (see also Bull & Scerif, 2001; Espy et al., 2004). In a study by Blair and Razza (2007) inhibitory control was significantly related to early mathematical ability. Finally, the ability to switch between tasks (*set shifting*) is required when alternating between different operations (e.g., adding and subtracting), for example when solving complex mathematical problems. Set shifting is not acquired until the end of the preschool period and is supposed to be more important later in development (Bull et al., 2008) for learning new concepts and procedures (Cragg & Gilmore, 2014).

However, it should be noted that studies in young children often fail to find the componential structure of executive functions (e.g., Wiebe, Espy, & Charak, 2008), suggesting a more unitary structure of executive functions during childhood. Nonetheless, the ability to deal with conflict during information processing together with the ability to focus attention and ignore irrelevant information