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Early numerical development and the role of non-symbolic and symbolic skills

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A B S T R A C T

For learning math, non-symbolic quantity skills, symbolic skills and the mapping between number symbols and non-symbolic quantities are all important precursors. Little is known, however, about the interrelated development of these skills. The current study focuses on numerical development by: (a) investigating the structure of non-symbolic, symbolic and mapping skills; and (b) examining the role of non-symbolic versus symbolic numerical skills.

Non-symbolic, symbolic and mapping skills of 69 children were assessed at age 4, 5 and 6. Results provided evidence for: (a) the developmental course of all numerical skills showing distinguishable skills at a younger age versus an integration of skills in older children; and (b) the predominant role of symbolic skills versus the subordinate role of non-symbolic skills in the development of mapping skills. Moreover, symbolic and mapping skills were found to be important predictors for math performance. These results provide new insights in early numerical development.

1. Introduction

In early numerical development children have to learn the connection between number symbols and their corresponding quantities; they have to understand that ‘3’ matches a set of three objects (whether they are fingers, apples or toys) and that ‘89’ is a bigger number than ‘23.’ These skills are referred to as mapping skills. Mapping skills become more accurate during development and underlie a wide range of math tasks (Booth & Siegler, 2008; Siegler & Booth, 2004) but little is known about the early development and precursors of these mapping skills. A common idea in the existing literature is that both *non-symbolic* quantity skills and *symbolic* skills are prerequisites for the mapping of number symbols to non-symbolic quantities (e.g. Gilmore, McCarthy, & Spelke, 2010; Jordan, Glutting, & Ramineni, 2010). Longitudinal evidence for this idea, however, is scarce and, moreover, it is unclear how non-symbolic and symbolic skills contribute to the (early) development of mapping skills. The aim of the current study, therefore, is twofold. First, the structure of a range of numerical skills is examined at different ages in order to examine the developmental course of non-symbolic, symbolic and mapping skills. Second, the contribution of both non-symbolic and symbolic numerical skills to the development of mapping between number symbolic and quantities is examined. By focusing on the developmental relations between non-symbolic, symbolic and mapping skills this longitudinal study will provide new insights in early numerical development.

1.1. Numerical development: non-symbolic, symbolic, and mapping skills

Current understandings of numerical development assume that both non-symbolic and symbolic skills and the mapping of numbers to quantities are important skills for math learning. In this first part of our paper, we will provide a description of these concepts and we will discuss their interrelations.

Non-symbolic understandings of numerical quantities are demonstrated to be already present in infants (Barth et al., 2006; Dehaene, 2001; Wood & Spelke, 2005; Xu, Spelke, & Goddard, 2005). Dehaene (2001) suggested that this non-symbolic magnitude knowledge is based on a cognitive system dedicated to processing quantity information. Within this system, quantities seem to be ordered spatially on a metaphorical mental number-line with increasing acuity throughout development (Halberda & Feigenson, 2008). On this mental number-line, each quantity has a specific range or position with smaller quantities placed at the left end of the line and bigger quantities placed on the right (Dehaene, Bossini,

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& Giraux, 1993; Fischer, Castel, Dodd, & Pratt, 2003; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006). The ability to understand and manipulate numerical magnitudes is referred to as *non-symbolic skills* in the current study.

Although these non-symbolic skills are believed to be innate, *symbolic skills* are believed to be culturally based acquired skills. These acquired numerical skills concern the ability to represent numbers verbally as strings of words and visually as strings of Arabic number symbols but do not contain any semantic information about the meaning of the number words and symbols (Dehaene & Cohen, 1995). These verbal and visual skills together are referred to as *symbolic skills* in the current study and address the ability to recite the counting sequence or identify number symbols without connection to the corresponding quantities.

Between the ages of 3.5 and 8 years children not only gain knowledge in reciting the counting sequence but they also show progress in focusing on numerosity in a set of objects which results in new understandings that number symbols are connected to quantities (Aunio, Hautamäki, Heiskari, & Van Luit, 2006; Hannula & Lehtinen, 2005; Wynn, 1992). Dehaene (2001) suggested that this development is facilitated by transcoding processes enabling information to be translated from non-symbolic to symbolic format and vice versa, providing the number symbols with a non-symbolic magnitude meaning. These processes eventually lead to a flexible integration of the different codes, resulting in numerical skills in which number words and symbols are mapped on their corresponding magnitude (Dehaene, 2001; Mundy & Gilmore, 2009). A frequently used task to measure mapping skills is a number-line task in which children need to estimate the position of a given number on a horizontal number-line. The idea behind this number-to-position task is that non-symbolic quantity information is needed for accurate placement of symbolic number symbols. When the mapping between number symbols and non-symbolic quantities is not yet fully developed, children have trouble with estimating the correct positions of numbers on a number-line. Evidence for this idea is provided by a large amount of studies focusing on performance on the number-line task. Various studies found evidence for a developmental shift from inaccurate logarithmic placements to accurate linear placements on the number-line task (Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler & Opfer, 2003). Older children, in whom mapping skills were more developed, were able to estimate number position more accurately than younger children in whom the integration of the different codes into mapping skills might not have taken place yet. The development of accurate mapping between number symbols and non-symbolic quantities is important for learning more advanced math operations such as addition or subtraction (Booth & Siegler, 2008; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegler & Booth, 2004).

Although previous studies provided evidence for the importance of non-symbolic, symbolic and mapping skills in math learning and revealed their developmental trajectories, studies examining the developmental relations between these skills are scarce. An assumption that can be made based on the existing literature is that numerical skills develop from separate systems for the processing of non-symbolic and symbolic information to an integrated system which enables adults to process numerical information automatically (Dehaene, 2001). The first question that is addressed in the current study is how numerical skills develop in young children. Are non-symbolic, symbolic and mapping skills distinguishable in young children, indicating that there are different systems for symbolic and non-symbolic numerical processing? And do these skills become gradually integrated into one system for numerical processing in the course of development? Therefore the first aim of this paper is to examine the developmental course of non-symbolic, symbolic and mapping skills.

1.2. Precursors in the development of mapping skills

The second aim of this paper is to gain insight into the relative role of both non-symbolic and symbolic numerical skills in the development of mapping skills. Although several studies showed that both *non-symbolic* and *symbolic* skills are important in developing accurate mapping between number symbols and quantities (e.g. Gilmore et al., 2010; Jordan et al., 2010), others advocate that either *non-symbolic* skills (e.g. Dehaene, 2001) or *symbolic* skills (e.g. De Smedt & Gilmore, 2011) play a dominant role in this development.

Our first Hypothesis is that non-symbolic magnitude knowledge provides a meaning to number symbols and it is assumed, therefore, that *non-symbolic* skills have a major effect on mapping skills and underlie all further math development. An influential advocate of the importance of non-symbolic skills in the development of mapping skills is Dehaene (2001). Based on the triple-code model (Dehaene, 1992; Dehaene & Cohen, 1995) in which it is assumed that numerical information can be processed mentally in three formats or 'codes', Dehaene (2001) formulated a developmental hypothesis in which it was proposed that all children are born with a system for processing non-symbolic quantity information ('analgue-code'). Exposure to language and math education leads to the acquisition of number words ('verbal code') and number symbols ('visual code') which are eventually mapped onto their corresponding quantity, assuming that the non-symbolic skills provide meaning to number symbols which are needed in all math tasks. This claim, emphasizing the importance of non-symbolic skills, is also supported by Von Aster and Shalev (2007). They proposed that non-symbolic understandings of magnitude form a necessary precondition for learning to associate a perceived number of objects with symbolic number words or number symbols. Acquired symbolic skills, in turn, constitute a precondition for the development of mapping skills. Although longitudinal evidence for these developmental models is scarce, evidence for the importance of non-symbolic skills in learning math is provided by several studies from different research lines.

A first line of evidence comes from research focusing on identifying the determinants of dyscalculia. Several authors confirmed the 'number module deficit hypothesis' assuming that math problems arise from deficits in non-symbolic skills. In these studies, symbolic and non-symbolic comparison tasks are used to examine differences in performance between dyscalculic children and their typically achieving peers. Group differences on both tasks indicated that a deficit in understanding and processing non-symbolic numerical information might underlie the math problems of dyscalculic children (Landerl, Fussenegger, Moll, & Willburger, 2009; Mussolin, Mejias, & Noël, 2010; Piazza et al., 2010).

Other evidence for the importance of non-symbolic skills in early numerical development comes from studies showing that non-symbolic skills underlie performance in several numerical tasks. On a symbolic task, 5-year-olds spontaneously used non-symbolic skills to manipulate symbolic stimuli, indicating that the non-symbolic knowledge was used for a symbolic task (Gilmore, McCarthy, & Spelke, 2007). Moreover, relations were found between non-symbolic skills and math performance within children 5–8 years old (Desoete, Ceulemans, De Weerdt, & Pieters, 2010; Gilmore et al., 2010; Inglis, Attridge, Batchelor, & Gilmore, 2011).

Nonetheless, some studies also question the role of non-symbolic skills (e.g. De Smedt & Gilmore, 2011; Krajewski & Schneider, 2009a; Landerl & Kölle, 2009; Rousselle & Noel, 2007).