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Typical and atypical development of basic numerical skills in elementary school

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ABSTRACT

Deficits in basic numerical processing have been identified as a central and potentially causal problem in developmental dyscalculia; however, so far not much is known about the typical and atypical development of such skills. This study assessed basic number skills cross-sectionally in 262 typically developing and 51 dyscalculic children in Grades 2, 3, and 4. Findings indicate that the efficiency of number processing improves over time and that dyscalculic children are generally less efficient than children with typical development. For children with typical arithmetic development, robust effects of numerical distance, size congruity, and compatibility of ten and unit digits in two-digit numbers could be identified as early as the end of Grade 2. Only the distance effect for comparing symbolic representations of numerosities changed developmentally. Dyscalculic children did not show a size congruity effect but showed a more marked compatibility effect for two-digit numbers. We did not find strong evidence that dyscalculic children process numbers qualitatively differently from children with typical arithmetic development.

Introduction

The cognitive representation of numbers has been the focus of research from several perspectives. First, in adults, a complex neurocognitive network specifically attuned to processing of numbers and magnitudes that is also active during mental arithmetic could be identified and is continuously further specified (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003). Second, empirical evidence indicates that a basic understanding of magnitude is apparent in infants (Antell & Keating, 1983; Starkey & Cooper,

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1980; Wynn, 1992; Xu & Spelke, 2000) and in various animals (see Brannon, 2005, for a review), suggesting that this understanding is evolutionary based and is an integral part of human cognition. The basic skills in magnitude processing that could be demonstrated during infancy are often interpreted as core knowledge underlying all further developments in number processing and arithmetic skills. Indeed, recent research suggests that an inborn deficit in this number module (Butterworth, 1999) or number sense (Dehaene, 1992; Wilson & Dehaene, 2007) may underlie specific problems in the development of arithmetic skills, generally termed as dyscalculia. A number of recent studies have demonstrated that individuals with dyscalculia perform very poorly on even the simplest tasks requiring number processing such as comparing or naming digits, reciting the counting sequence, and counting small numbers of dots as quickly as possible (Landerl, Bevan, & Butterworth, 2004; Landerl, Fussenegger, Moll, & Willburger, 2008; Rousselle & Noël, 2007).

In spite of the high relevance of basic numerical processing for further developments in arithmetic skills, we do not know much about typical and atypical trajectories in the development of these skills (Ansari & Karmiloff-Smith, 2002). Ideally, one would follow numerical development longitudinally from early infancy through to the central steps in the development of arithmetic skills that are usually mastered during the first grades in elementary school. However, although such an approach would certainly help us to better understand the early developmental steps in numerical processing, it would currently be impossible to differentiate between children with good arithmetic skills and those with poor arithmetic skills because we have currently no good means to identify arithmetic problems before they become apparent during the elementary school years (but see Mazzocco & Thompson, 2005, for promising findings of early prediction). Furthermore, children who experience problems in doing arithmetic in Grade 1 are not necessarily dyscalculic and may catch up in Grade 2 (Geary, Hamson, & Hoard, 2000). From Grade 2 onward, arithmetic skills seem to develop with high stability (Jordan, Hanich, & Kaplan, 2003).

As a further step toward the ambitious enterprise to better understand typical and atypical trajectories of basic numerical skills, we report here findings from a large-scale study assessing basic numerical skills in more than 400 elementary school students in Grades 2, 3, and 4. This large group of typically and atypically developing children were given measures of basic numerical processing that have been used with children as well as adults in earlier studies. In contrast to earlier developmental studies that looked at response accuracy in simple number processing tasks and often needed to deal with ceiling effects even among children with poor arithmetic skills from a certain age onward (e.g., Geary, Hoard, & Hamson, 1999), we used response time (RT)-based tasks allowing us to inspect developments in the efficiency of processing of numbers and magnitudes. In particular, using RT-based tasks enabled us to inspect the development of standard effects of number processing that are consistently reported in adults (see below) and are informative with respect to how numbers and magnitudes are represented and processed in our cognitive system. A practical advantage of the low level of difficulty of our task battery was that it ensured that even the dyscalculic participants were highly motivated to perform well.

Already during infancy, a certain ability to differentiate between item sets of different numerosities can be observed (Feigenson, Dehaene, & Spelke, 2004; Starkey & Cooper, 1980; Xu & Spelke, 2000; but see Clearfield & Mix, 1999, for a different view). This ability is not limited to small number sets but rather allows infants to differentiate between larger sets as well if the ratio between the two numerosities is 2:1. This skill improves rapidly, and by 9 months of age the ratio of numerosities that can be differentiated has developed to 3:2 (Lipton & Spelke, 2003). The deficient number module account of dyscalculia implies that problems in the nonverbal estimation and comparison of nonsymbolic item sets should be evident in children with serious arithmetic problems; indeed, Landerl and colleagues (2008) recently demonstrated higher RTs in 8- to 10-year-old dyscalculic children compared with typically developing children in a magnitude comparison task requiring participants to select the numerically larger of two displays of yellow squares experimentally controlled for surface. Whereas the sample reported by Landerl and colleagues was too small to allow inspection of age differences, such differences are the main focus of the current analysis, which employed the very same experimental paradigm. In general, we assume that it is easier to differentiate between two collection sets if the numerical distance between the two sets is large (e.g., 26 vs. 55 squares) than when it is small (e.g., 26 vs. 38 squares); thus, we predict finding an effect of numerical distance. A plausible developmental