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Number line estimation from kindergarten to grade 2: A longitudinal study

Magda Praet, Annemie Desoete*

Ghent University, Belgium

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ABSTRACT

A bulk of evidence supports the association of number line estimations using Arabic digits and dots with math learning. Surprisingly few studies have been conducted to explore the relationship between estimations using number words and mathematics. The present study expands previous findings by investigating estimations in three formats (Arabic digits, dots and number), adding language as predictor and by focusing at timed and untimed math learning. A sample of 132 children was followed from kindergarten till grade 2. Results reveal variability in estimation accuracy and errors declining with age and instruction in all children. In addition, our findings suggest that Arabic numerals have a more linear distribution than number words. Moreover, our findings suggest that language explains variation in kindergarten but not in evolution and, more in particular, untimed math achievement can be predicted by number line estimation. Implications for assessment, prediction of math learning and instruction are discussed.

1. Introduction

There has been extensive research on number line estimation (Bertelli, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Schneider et al., 2008; Slusser, Santiago, & Barth, 2013) and the relationship with mathematics. However, most of these studies have a cross-sectional design, using dots or Arabic numbers (e.g., Ashcraft & Moore, 2012; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Moeller, Pixner, Kaufmann, & Nuerk, 2009; Muldoon, Towse, Simms, Perra, & Menzies, 2013; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013) as stimuli for the estimations. In addition to estimation, the value of including language as predictor for mathematics has been stressed (Praet, Titeca, Ceulemans, & Desoete, 2013; Sarnecka, Kamenskaya, Yamana, Ogura, & Ydovina, 2007; Wiese, 2003). However surprisingly few studies have been conducted to explore the combined effect of these predictors on math learning. This study addresses this gap and has the unique scientific merit of focusing on age-related changes in children's numerical estimate accuracy and distribution using three different format types (stimuli as Arabic numerals, spoken number words, and dot patterns) at five measuring points (from kindergarten to grade 2), with children becoming more familiar with numbers up to 100 (learning to count in kindergarten, deal with numbers from 0 to 20 in grade 1 and up to 100 in grade 2). In addition this study expands previous findings, by investigating the prediction for timed and untimed math learning. Insight about the detailed nature of underlying number representations can inform targeted assessment and might have educational implications for learning and instruction researchers and professional addressing kindergarteners at risk for mathematical learning difficulties.

1.1. Numerical estimation and development

It is widely accepted that there is a gain in accuracy of number line judgments on a 0–100 interval with increasing formal schooling. In addition research indicates a developmental transition from a logarithmic distribution of the representation of numbers (with children experiencing a larger distance between 2 and 3 than between 18 and 19) to a more linear function as the result of a better one-to-one correspondence between the value being judged and its estimate, from preschool to primary school (Siegler & Booth, 2004; Siegler & Opfer, 2003). The linearity of judgments is often positively correlated with math learning (Ashcraft & Moore, 2012; Siegler & Booth, 2004).

Dehaene (1992, 1997), Dehaene and Cohen (1995) stated in his triple code model that number representation takes place in three different ways, with three different formats, located at

* Corresponding author. Experimental Clinical and Health Psychology Developmental Disorders, Ghent University and Artevelde University college, Belgium.
E-mail addresses: annemie.desoete@ugent.be, annemie.desoete@telenet.be (A. Desoete).

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three different brain regions. Firstly, there is a (symbolic) visual system where numbers are encoded as strings of Arabic digits (e.g., '14') needed for multidigit calculation and parity judgments. Secondly, there is a (symbolic) verbal system where numbers are represented as sequences of number words (e.g., 'fourteen') lexically, phonologically and syntactically. The third system uses (asymbolic) analog magnitude codes as non-verbal semantic size and distance relations between (e.g., a collection of 14 dots).

Although evidence was found for a general, modality-independent representation across different kind of magnitudes, such as numbers, quantities of objects, lengths and durations (Barth, Kanwisher, & Spelke, 2003; Huntley-Fenner & Cannon, 2000), some studies have found a relationship between symbolic tasks but not between non-symbolic number comparison skills and math learning (e.g., De Smedt, Noel, Gilmore, & Ansari, 2013; Holloway & Ansari, 2009; Mundy & Gilmore, 2009). In addition, up to now, most studies focussed on non-symbolic magnitude representation, sometimes in combination with the symbolic representation with Arabic numbers (e.g., Ashcraft & Moore, 2012; Geary et al., 2008; Moeller et al., 2009; Muldoon et al., 2013; Sasanguie et al., 2013). On basis of such data, it is often unclear whether it is the Arabic number or number words processing that is important for math learning. Finally, Sasanguie et al. (2013) suggested an association between estimation and a general curriculum-based math test but not with a timed math fluency test. Therefore we might question ourselves if the used format to test number estimation or math learning does not affect an influence on the observed relationships.

The last decades, several researchers have studied the relationship between estimation and mathematics achievement. Recently, Muldoon et al. (2013) revealed in a longitudinal study that 5-year olds with less-accurate internal representations of numbers tested on 4 occasions at 3 months intervals were disadvantaged on some early math tasks, such as recognizing number names and numerals, identifying quantitative relationships, matching magnitudes and quantities or solving easy word problems, compared to peers with better quality representations. However, the question of whether it is the Arabic number or number words processing that is important for math learning and the relationship with math fluency and untimed math learning remains unresolved. Since the other existing research are cross-sectional studies (Ashcraft & Moore, 2012; Berteletti, Lucangeli, & Zorzi, 2012; Booth & Siegler, 2006; Ebersbach, Luwel, Frick, Onghena, & Verschaffel, 2008; Holloway & Ansari, 2009; Sasanguie et al., 2013; Schneider et al., 2008; Siegler & Booth, 2004; Slusser et al., 2013), predictions on estimation accuracy and distribution growth are difficult to make.

1.2. Math achievement and language

Although children process numbers long before the acquisition of language (Dehaene, 2001), the value of including language has recently been stressed in the prediction of numeracy development (Praet et al., 2013; Purpura, Hume, Sims, & Lonigan, 2011; Romano, Babchishin, Pagani, & Kohen, 2010; Sarnecka et al., 2007; Wiese, 2003).

Having a larger nominal vocabulary was found to be helpful in the acquisition of number words (Negen & Sarnecka, 2012). In addition some studies (Barner, Chow, & Yang, 2009; Negen & Sarnecka, 2012) revealed that general measures of language development also predicted number-word knowledge, although other studies (e.g., Ansari et al., 2003) did not find such a link. Whether or not language helps children in kindergarten to solve mathematical problems, remains a point of discussion.

1.3. The current study

To summarize, empirical evidence for age-related changes in estimations in three formats, adding language as predictor and focusing at timed and untimed mathematic achievement is lacking. Moreover, very few studies examined these skills in a longitudinal design from kindergarten till grade 2.

This study addresses the following two major research questions: (a) is the accuracy and distribution of the estimation of the position of numbers using different formats (stimuli as Arabic numerals, spoken number words, and dot patterns) mirroring the familiarity with numbers and predicting untimed and timed math learning? and (b) Does language explains variation in the growth curves?

For the first research question four additional questions or hypotheses were formulated. We expected a better accuracy in the estimation of the position of numbers in older children mirroring their familiarity with numbers (Hypothesis 1). Considering the format-independency hypothesis, similar results on the estimation with Arabic numerals, spoken number words, and dot patterns were expected (Hypothesis 2). In line with the developmental shift, we expected a kindergarteners estimating in a logarithmic manner, and children in grade 1 and grade 2 following a more linear curve (Hypothesis 3). Finally different predictions for the processing of untimed calculation and timed fact retrieval tasks are expected (Hypothesis 4).

For the second research question changes over time were expected with language explaining some of the variation in the growth curves (Hypothesis 5).

2. Methods

2.1. Participants and procedure

The children in this study ($N = 132$, 53% girls) were Dutch-speaking children from five kindergartens serving children from families with working and middle-class-socio-economic backgrounds. Written parental consent to participate in the study was obtained for all children.

All children were individually tested in kindergarten at measurement time 1 (March kindergarten = time period T1) in a quiet room of the school to obtain measures of intelligence, number estimation and early calculation skills.

Measurements 2 and 3 took place in grade 1 (November grade 1 = time period T2 getting instruction on numbers 0–10, June grade 1 = time period T 3 getting instruction on numbers 0–20). All children were individually tested on their number estimation and ability to solve simple calculations (T2 and T3) as well as on their ability to retrieve number facts (T3).

Due to constraints in access to schools and the children attending them, it was not feasible to collect on all children on all five time points. On half of the children data were collected on all five time points. They were tested in grade 2 (October grade 2 = time period T4 rehearsal of instruction on numbers 0–20, January grade 2 = time period T5 getting instruction on numbers 0–100) on number estimation (T4 and T5) and on their ability to calculate (T5).

2.2. Measures

2.2.1. Intelligence

Intelligence was assessed in kindergarten (at T1) with the Wechsler Preschool and Primary Scale of Intelligence or the WPPSI-III-NL (Hendriksen & Hurks, 2009; Wechsler et al., 2002). Children completed the three core verbal tests (information, vocabulary, and