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Number sense in kindergarten children: Factor structure and working memory predictors

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ABSTRACT

In the current study, the factor structure of number sense, or the ability to understand, use, and manipulate numbers, was investigated. Previous analyses yielded little consensus concerning number sense factors, other than a distinction between nonsymbolic and symbolic processing. Furthermore, associations between number sense factors and working memory components were investigated to gain insight into working memory involvement in number sense. A total of 441 Dutch kindergartners took part in the study. The factor structure of number sense and associations with working memory were tested using structural equation modelling. Results indicated that there was a distinction between nonsymbolic and symbolic number processing. Nonsymbolic processing was predicted by central executive performance, and symbolic processing was predicted by both central executive and visuospatial sketchpad performance. This implies that symbolic and nonsymbolic processing are distinguishable at this age, and that working memory involvement in symbolic processing is different from that in nonsymbolic processing.

1. Introduction

How does a child learn to understand that the same number word can refer to any set of the same quantity, without that set having to consist of the same elements, or the elements even needing to be directly observable? The term usually employed to describe this understanding of number and quantity is number sense (NS), or the ability to mentally represent and manipulate number and quantity (Dehaene, 1992, 2001), resulting in the ability to compare and manipulate numbers (Jordan, Glutting, Ramineni, & Watkins, 2010). Despite this rather narrow definition, a large variety of declarative number-related skills is seen as indicative of NS, with little agreement with regard to which components should be incorporated into the definition of number sense (e.g., Jordan, Glutting, Ramineni and Watkins, 2010; Malofeeva, Day, Saco, Young, & Ciancio, 2004). A dominant view is that whilst developing NS skills, children gradually learn to count, to use number words to describe quantities, to compare between numbers and quantities, and eventually, to manipulate numbers through calculation. All the while, both their intuitive and declarative knowledge of numbers grows.

NS at an early age has been denoted as the most important predictor of later mathematics performance: more important than general intelligence, and still present when controlling for other measures such as working memory (e.g., Geary, Hoard, Nugent, & Bailey, 2013; Mazzocco, Feigenson, & Halberda, 2011). Similarly, problems in early NS may precede long-lasting problems in mathematics performance throughout the academic career of a child (Ansari & Karmiloff-Smith, 2002; Butterworth, 2005). In the past decades, research concerning the components of NS, its predictive role for later performance, and the possibilities to remediate delays in NS has been expanded (e.g., Dyson, Jordan, & Glutting, 2013; Toll & Van Luit, 2013a). The present study builds on current understandings of NS and aims to investigate the factor structure of NS and the predictive role of working memory (WM).

1.1. Components of number sense

Although research concerning NS has recently increased, there is limited consensus with regard to its definition. Dehaene (1992, 2001) stressed the intuitive capacity to mentally represent quantities, but other definitions focus on declarative knowledge of numbers, and the ability to compare between and manipulate them, as evidenced by diverse batteries of quantity-related tests (Jordan, Glutting, Ramineni, & Watkins, 2010; Malofeeva et al., 2004). Also, a limited number of studies have targeted the factors underlying the construct. A total of three factor-analyses of NS have been conducted over the past few years: one produced a two factor model distinguishing between number-related skills and rapid naming (Lago & DiPerna, 2010). A second factor analytical study made a distinction between three factors: symbolic NS, nonsymbolic NS, and the mapping between nonsymbolic and symbolic representations (Kolkman, Kroesbergen, & Leseman, 2013). A third study reported no less than five factors of NS, being nonsymbolic

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comparison, symbolic comparison, symbolic labelling, rote counting, and counting knowledge (Cirino, 2011). All three studies concerned NS measured in kindergarten, but the only overlap between the produced factors is the distinction between symbolic and nonsymbolic processing found both in the study by Kolkman, Kroesbergen, and Leseman (2013) and Cirino (2011).

Despite the small number of factor analyses and the lack of overlap between the available models, many assertions have been made about components of NS. A distinction between symbolic and nonsymbolic skills has been made in various studies (Defever, Sasanguie, Gebuis, & Reynvoet, 2011; Holloway & Ansari, 2009; Jordan, Glutting, & Ramineni, 2010; Sasanguie, Defever, Maertens, & Reynvoet, 2014; Vanbinst, Ghesquière, & De Smedt, 2012). Nonsymbolic skills are generally thought to underlie symbolic skills, meaning that symbolic quantities are thought to be mapped onto nonsymbolic quantity representations (Barth, La Mont, Lipton, & Spelke, 2005; Dehaene, 1992; Mundy & Gilmore, 2009). However, it has recently been argued that the formation of nonsymbolic skills is dependent on symbolic skill development, instead of the other way around (De Smedt, Noël, Gilmore, & Ansari, 2013; Piazza, Pica, Izard, Spelke, & Dehaene, 2013). Others have argued that symbolic and nonsymbolic skills are not mutually dependent in any direction (Lyons, Ansari, & Beilock, 2012; Sasanguie et al., 2014). Moreover, arguments against nonsymbolic NS as a unitary construct have been made (Sasanguie & Reynvoet, 2013).

The lack of consensus regarding the factor structure of NS is contrasted by a small consensus that NS, like mathematical skill, can be predicted by WM capacity. This claim has been investigated in typically developing children (Friso-van den Bos, Kolkman, Kroesbergen, & Leseman, 2014; Kyttälä, Aunio, Lepola, & Hautamäki, 2014) and children with special educational needs (Kleemans, Segers, & Verhoeven, 2011; Kroesbergen, Van de Rijt, & Van Luit, 2007; Kyttälä, Aunio, & Hautamäki, 2010; Toll & Van Luit, 2013b).

1.2. Components of working memory

The term working memory refers to a storage and processing unit consisting of several components. The most influential model of WM is the multi-component model that identifies three main storage and processing units (Baddeley, 2007; Baddeley & Hitch, 1974). The phonological loop is responsible for the temporary storage of verbal and auditory information, and dependent on a memory trace that is hypothesised to fade without rehearsal of information. The phonological loop is involved in language comprehension and acquisition, and would, for example, allow a child to understand verbal instructions about number. A second component, the visuospatial sketchpad, is also responsible for temporary storage, but in this case for visual and spatial information. This component stores information about shape and location, but is also responsible for visual imagery, for example, when performing mental counting operations. A third component, the central executive, concerns an attentional control system capable, for example, of evaluating pieces of information for appropriate decision making (Baddeley & Hitch, 1974), such as counting up or counting down after a number of objects has been manipulated.

1.3. Working memory predicting number sense

WM is regarded as the most important domain-general predictor of mathematics at primary school age, both concurrently (Bull & Scerif, 2001; Van der Ven, Kroesbergen, Boom, & Leseman, 2012), and longitudinally (Passolunghi, Mammarella, & Altoè, 2008; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011; Van der Ven et al., 2012). Evidence is also available that part of the variation in NS performance is explained by WM functioning. There are both associations between NS performance and WM functioning within groups of typically achieving children (Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Lee et al., 2010; Noël, 2009), and differences in WM between children with delays in NS and typically developing children (Jenks et al., 2007; Kleemans et al., 2011). A meta-analysis of the associations between NS performance and central executive functioning reported significant associations, but it was noted that more research regarding the associations between domain-general skills and NS was necessary because of a small number of studies investigating these relations, and because of unexplained variation between effect sizes (Friso-van den Bos, 2013). Unexplained variation between effect sizes may indicate contradictory results in terms of size or direction of relations.

Indeed, associations between measures of NS and WM components seem contradictory, both within and between studies. For example, measures of the phonological loop have been found to be correlated with NS performance in some studies (e.g., Jordan, Glutting, & Ramineni, 2010) but not others (e.g., Costa et al., 2011; Kyttälä et al., 2010). The finding that phonological loop correlates with counting proficiency, but not conceptual NS (Jenks et al., 2007), indicates that part of the variation may be due to WM having differential predictive power for some measures of NS than for others. In a similar way, functioning of the visuospatial sketchpad has been found to statistically predict specific NS measures but not others (Barnes et al., 2011; Costa et al., 2011; Kleemans et al., 2011). This trend can also be found in associations between NS and central executive performance (Costa et al., 2011; Kyttälä et al., 2010; Lee et al., 2010). These associations are investigated in the current study.

1.4. The current study

The current study had two aims, both adding onto recent understandings of the development of NS and its predictors. The first aim was to investigate the factor structure of NS in a large and representative group of kindergarten children. Available factor analyses have yielded no consensus with regard to the factors of which NS consists, although a distinction between symbolic and nonsymbolic tasks has been made in two factor analytical studies (Cirino, 2011; Kolkman, Kroesbergen, & Leseman, 2013) and similar claims have been made in a multitude of theoretical papers (Defever et al., 2011; Holloway & Ansari, 2009; Jordan, Glutting, & Ramineni, 2010; Vanbinst et al., 2012). In the current study, the factor structure of NS was investigated using a large sample size and advanced analytical methods, using the distinction between symbolic and nonsymbolic processing as a starting point. Measures of number sense included measures of declarative knowledge, with a broader spectrum than proposed in Dehaene's original definition (1992), but consistent with research traditions (Jordan, Glutting, Ramineni, & Watkins, 2010; Malofeeva et al., 2004).

The second aim of this study was to investigate the associations between WM components (Baddeley & Hitch, 1974) and NS factors. Previous studies have reported associations between WM components and NS performance (Costa et al., 2011; Jenks et al., 2007; Kyttälä et al., 2010; Xenidou-Dervou, Van Lieshout, & Van der Schoot, 2013), but there is little consensus with regard to which WM component can predict performance. Moreover, different components of WM may have diverging relevance for distinguishable factors of NS, because WM demands of tasks with different properties may vary (for example, nonsymbolic tasks may rely heavily on visuospatial skills; Kolkman, Kroesbergen, & Leseman, 2014). Nevertheless, we expected WM to significantly explain variance in all factors of NS because of the need for using the WM system to process information such as verbal instruction in acquiring and measuring NS skills.

2. Method

2.1. Participants

Data were collected in 441 typically performing kindergarten children. Children were from 24 schools in various municipalities in the Netherlands. The mean age of the participants at the start of the study