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Kindergarten children's symbolic number comparison skills predict 1st grade mathematics achievement: Evidence from a two-minute paper-and-pencil test

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ABSTRACT

Basic numerical skills provide an important foundation for the learning of mathematics. Thus, it is critical that researchers and educators have access to valid and reliable ways of assessing young children's numerical skills. The purpose of this study was to evaluate the concurrent, predictive, and incremental validity of a two-minute paper-and-pencil measure of children's symbolic (Arabic numerals) and non-symbolic (dot arrays) comparison skills. A sample of kindergarten children (M_{age} = 5.86, N = 439) were assessed on the measure along with a number line estimation task, a measure of arithmetic, and several control measures. Results indicated that performance on the symbolic comparison task explained unique variance in children's arithmetic performance in kindergarten. Longitudinal analyses demonstrated that both symbolic comparison and number line estimation in kindergarten were independent predictors of 1st grade mathematics achievement. However, only symbolic comparison remained a unique predictor once language skills and processing speed were taken into account. These results suggest that a two-minute paper-and-pencil measure of children's symbolic number comparison is a reliable predictor of children's early mathematics performance.

1. Introduction

A growing body of research points to basic numerical skills as critical precursors of later mathematics achievement. In general, children who demonstrate a strong proficiency with basic numerical skills, such as being able to quickly and accurately state the larger of two symbolic numbers (7 vs. 3), tend to also demonstrate strong performance in more advanced mathematics tasks, including arithmetic (Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013), word problems (Fuchs et al., 2010), fractions (Mou et al., 2016), and geometry (Lourenco & Bonny, 2017). Presumably, this is due in part to the hierarchical nature of mathematics learning, where earlier learned skills serve as essential building blocks in the construction of more sophisticated mathematics understanding.

The consequences of low numeracy can be substantial, not only influencing one's educational attainment but also one's personal well-being and the associated economic costs. For example, a large study carried out in the UK revealed that low numeracy had more of negative influence on one's life chances than low literacy (Gross, Hudson, & Price, 2009). Low numeracy has been found to coincide with lower earnings, lower spending, poorer health outcomes, and increased trouble with the law (Parsons & Bynner, 2005). Furthermore, Ritchie and Bates (2013) found that numerical knowledge at seven is predictive of one's SES at the age of 42, even after controlling for the individuals' own IQ and the SES of the family which they were born into.

Given the importance of basic numerical skills for later educational and occupational success, it is crucial that educators have access to research-informed and reliable assessments of basic numerical competencies. Such assessment tools are necessary in order for teachers of young children to measure students' initial skills at the beginning of the school year, track growth over the course of the year, and perhaps most importantly, identify children in potential need of early intervention.

Although early numeracy and mathematics assessments do exist, most of these assessments are fairly complicated to administer and require considerable amounts of time. In order for assessments of young children's numerical skills to be of use to the practicing teacher, these assessments should necessarily be easy to administer and require little time. Although much headway has been made in providing teachers

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with such assessments in literacy (e.g., Diagnostic Reading Assessment (DRA); Beaver, 1968: Dynamic Indicators of Basic Early Literacy Skills (DIBELS); Good & Kaminski, 2002), the same cannot be said of early mathematics assessments (but see some recent advancements by Brankaer, Ghesquière, & De Smedt, 2017 and Purpura & Lonigan, 2015). Moreover, prior efforts to design and measure basic numerical skills have yet to test the ecological validity of such assessments. It remains to be demonstrated whether numerical assessments intended for teacher use are predictive of school mathematics (e.g., teacher assigned math grades). The present study aimed to address this gap.

1.1. Rationale and aims of current study

In this paper, we share the results of implementing a two-minute paper-and-pencil assessment of young children's basic numerical skills. The Numeracy Screener, as it is referred to hereafter, was specifically designed with the educator and researcher in mind, providing both parties with a quick and research-informed method of assessing young children's (K-3) basic numerical skills (for more information see: Nosworthy et al., 2013 and www.numeracyscreener.org). More specifically, the tool was designed to measure children's non-symbolic and symbolic comparison skills. In prior research, it was found that performance on both the symbolic and non-symbolic portions of the assessment were concurrently related to individual differences in arithmetic achievement across 1st to 3rd grade. However, when symbolic and non-symbolic comparison skills were entered in the same model – one that included other control variables – only performance on the symbolic comparison task accounted for unique variance in arithmetic (Nosworthy et al., 2013). Although these findings provide initial promise of the measure, further steps are necessary in order to further test the utility of the Numeracy Screener as a valid and reliable assessment tool. The current study aimed to extend our previous work by (a) increasing the sample size, (b) more narrowly defining a population of interest (kindergarten[1]), (c) testing both the concurrent and predictive validity of the instrument, (d) evaluating the test-retest reliability, (e) examining convergent construct validity by comparing performance to another common measure of magnitude processing (i.e., the number line estimation task), and (f) including school grades as an ecologically valid measure of mathematics achievement. Ultimately, the efforts of this work are directed towards the creation of a valid, reliable, and publicly available assessment tool of young children's basic magnitude processing skills. In working towards this goal, the central aim of the current paper was to examine how basic numerical skills at kindergarten concurrently and longitudinally relate to more formal school mathematics, including arithmetic and teacher-assigned math grades.

1.2. Overview of children's magnitude processing skills

1.2.1. Attempts to measure children's knowledge and representation of number

To date, efforts to identify early predictors of mathematical success have largely focused on children's numerical magnitude processing skills. Indeed, the study of children's magnitude processing skills has received concerted attention from researchers in cognitive neuroscience, psychology, and education alike (e.g., see De Smedt, Noël, Gilmore, & Ansari, 2013). Presumably, the reason for such convergence has to do with what numerical magnitude tasks are thought to reveal about individuals' underlying representations of number. That is, the accuracy and speed with which an individual can access the numerical magnitude of sets of objects (non-symbolic) or symbolic representations (e.g., 5 or 'five') is typically taken as an indicator of the strength and precision of one's representation of number. Arguably, the three most widely used tasks to measure such a process involve non-symbolic number comparisons, symbolic number comparisons, and number line estimation (e.g., see Schneider et al., 2017). It is for this reason that we selected these tasks in the context of the present study.

Both non-symbolic and symbolic number comparison paradigms are similar in that they involve comparing and identifying the larger of two quantities (be they symbolic, 5 vs. 3, or non-symbolic ∴· vs. ˙.˙) as quickly and accurately as possible. The ability to quickly access numerical magnitudes is fundamental to a range of mathematical tasks, including exact and approximate calculations. For example, to know that combining two sets of objects (●● + ●) results in a total sum that is greater than one set alone, requires attending to the numerosity of the sets and not some other feature, such as physical size or total area (e.g., ●● + ● = ● • • and not ⬤). Similarly, to know that 58 + 45 is either approximately 100 or exactly 103, requires the ability to access the numerical magnitude of the symbolic addends, 58 and 45. In both examples, access to numerical magnitudes and not some other property is the common and critical property involved in the calculation process. Despite the similarities, the two tasks differ in several key regards. The non-symbolic number comparison task is thought to serve as an index of one's Approximate Number System (ANS); an ancient and rudimentary ability to discriminate between non-symbolic numerical magnitudes that is available early in infancy (Xu & Spelke, 2000) and shared with other non-human species (Feigenson, Dehaene, & Spelke, 2004). Symbolic number comparison on the other hand provides a measure of one's understanding of number symbols and the exact quantities that they represent. Performance on this task is mediated through cultural experiences with the symbolic number system and thus takes time to develop and is not immediately available early in life (Núñez, 2017). Taken together, although both tasks are used to measure one's ability to access and make judgments about numerical magnitudes, the two tasks differ with respect to when and how the two systems become available for use. These differences are non-trivial and underscore critical questions and debate regarding the extent to which these two magnitude systems are related and interact with one another over development (e.g., De Smedt et al., 2013; Leibovich, Katzin, Harel, & Henik, 2017). Moreover, questions remain about how individual differences on symbolic and non-symbolic magnitude tasks are related to future mathematics achievement (e.g., see De Smedt et al., 2013).

Number line estimation tasks represent another way in which researchers have attempted to measure individuals' numerical magnitude as well as more general numerical reasoning skills (Schneider et al., 2017). The most common form of this assessment involves presenting participants with horizontal line flanked by two end-points (e.g., 0 and 100) and asking them to estimate the location of a given number (e.g., 73). This task involves the mapping of numerical magnitudes onto continuous space and has been of theoretical and practical interest as performance on this task has been used as an indicator of the accuracy and precision of one's 'mental number line' (Dehaene, 2011).

[1] In Ontario, kindergarten consists of a two-year play-based program. The first year of kindergarten is known as Junior Kindergarten and begins when children are 3 or 4 years of age; it is the equivalent of what other countries (e.g., the USA) refer to as pre-school. Senior Kindergarten begins when children are 4 or 5 years of age and is more in line with what other countries refer to as kindergarten (e.g., the USA). In the current study, our sample was drawn from Senior Kindergarten students; referred to in this paper as kindergarten students in an effort to ease communication and maintain standards with other countries. In this paper, we also distinguish between informal and formal education by referring to kindergarten as an example of informal education and 1st grade as an example of formal education. This decision is based on the play-based curriculum guidelines of the kindergarten program and the more formal expectations of 1st grade. However, we acknowledge that this distinction is somewhat arbitrary and dependent upon the teacher and does not preclude the possibility of formal learning opportunities that some kindergarten classrooms might afford.