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Logarithmic to linear shifts in Chinese children's representations of numerical and non-numerical order

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ABSTRACT

Most studies about the developing representation of numerical information and non-numerical ordered sequences involved Western children. It is not as certain that children from other parts of the world display a similar pattern. Moreover, the issue of gender differences was seldom considered. To shed more light on the above issues, we conducted four experiments involving a total of 322 1st and 2nd graders in Mainland China. Children either estimated the locations of numbers on number lines or the locations of months on month lines. Across four experiments, children produced estimates consistent with a linear function for smaller numbers. For larger numbers and months, younger children produced estimates consistent with a logarithmic function but older children's estimates were best fitted through a linear function. There were complex differences between boys and girls: Overall, whereas boys were more accurate estimating numbers, girls were better at estimating months. In conclusion, the representation of numerical order in Chinese numbers mirrored the representation of numerical order in Arabic numbers, demonstrating the universal developmental pattern of numerical representation from the less accurate logarithmic function to the more accurate linear function. Also, like Western children, Chinese children's representation of non-numerical order showed the same developmental pattern as numerical order, although this ability appeared to be first acquired in the numerical domain.

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1. Introduction

It seems that in children's mental representation of magnitude, smaller values are more distant from one another than larger ones. For example, Arabic numerals 2 and 3 seem more distant from each other than 18 and 19 are. This interesting observation came from children's performance on numerical estimation using number lines (e.g., Booth & Siegler, 2006; see also Siegler & Opfer, 2003).

Typically, children were shown a horizontal number line, labeled 0 on the left and 100 (or 1000) on the right. In the number-to-position (NP) version of the task, children were given a number, for example 20, and asked to show where that

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Fig. 1. An example of Chinese number-to-position (CNP) task line (Arabic numeral equivalents are only inserted beneath the Chinese in parentheses to improve understanding for non-Chinese readers of this article: The Arabic numerals were not on the actual CNP task lines used).

value was located on the number line. Kindergartners usually chose a location by drawing a hatch mark closer to where 50 belonged. More generally, younger children produce estimates that are best fitted by a logarithmic function (Booth & Siegler, 2006). In the alternate version of the task, the position-to-number (PN) task, the hatch mark was already placed on the number line and children were asked to estimate its numerical value. Therefore, if the hatch mark was at position 50, a kindergartner might estimate its value to be 20. For the PN task, younger children often produce estimates that are best fitted by an exponential function (essentially a mirror image of the logarithmic function in the NP task).

These patterns led Siegler and others (e.g., Booth & Siegler, 2006; Siegler & Opfer, 2003) to conclude that the underlying mental representation of magnitude is an unevenly spaced logarithmic or "compressed" mental number line in which smaller values are spaced farther apart than they should be and larger values are compressed closer together than they should be: This is referred to as the Logarithmic Ruler Model (e.g., Dehaene, 1997; Siegler & Opfer, 2003). There are multiple theories that address the accuracy of numerical representation: Along with the Logarithmic Ruler Model, the Accumulator Model (Gibbon & Church, 1981) also stipulates that numerical representation is approximate and imprecise. The Linear Ruler Model (Case & Okamoto, 1996), in contrast, suggests that numerical representation is ultimately linear and thus accurate. But do people use a single model of numerical representation depending on their developmental period, or do they use multiple models of numerical representation?

Siegler (1996) believes that even young children have the ability to represent numbers in various modes. The overlapping waves theory (Siegler, 1996) was subsequently put forth to depict children at any given age as knowing beings who are able to use a variety of approaches (i.e., strategies, rules, or representations). These approaches often compete with one another for use, with each approach more or less adaptive depending on the problem and situation. The overlapping waves theory differs from other theories on representational development, such as stage theories (e.g., Bruner, Olver, & GreenWeld, 1966), incremental theories (e.g., Brainerd, 1978), and early competence theories (e.g., Gelman & Gallistel, 1978): It posits that individuals usually know and use multiple strategies and representations (rather than a single one), and that people are able to choose among the various approaches.

Based on the overlapping waves theory, the log discrepancy hypothesis (Opfer & Siegler, 2007) can be derived. This hypothesis states that experiences promote the extension of linear representation to new numerical context, as long as the experiences highlight discrepancies between logarithmic and linear representations of numerical magnitudes and make clear the appropriateness of the linear representation in the new context. If this hypothesis is correct, and improvement in estimation stems from the substitution of one representation for another, then changes in pattern of estimation may occur abruptly rather than gradually, and can occur across a broad range of numerical values rather than localized to the numerical range on which feedback is given. Also, the log discrepancy hypothesis implies that when people display context-dependent and varied levels of representational abilities, experiences that accentuate the benefits of the more advanced representational approach may bring about a rapid substitution of the more advanced approach for the less advanced one.

Through the years, the overlapping waves theory has been supported by a great deal of empirical data (e.g., Berteletti, Lucangeli, & Zorzi, 2010; Siegler & Booth, 2004; Siegler & Opfer, 2003). However, the vast majority of this line of research was conducted using Western children. One exception was Siegler and Mu (2008), who compared the performances of kindergarteners from China and the U.S. on a number-to-position task using number lines anchored at 0 and 100: Whereas kindergarteners from the U.S. evidenced a logarithmic numerical representation, Chinese kindergarteners represented the same numbers linearly, demonstrating Chinese children's more advanced numerical abilities. Another exception was Zhou, Mo, and Wen (2009), who found in a sample of Chinese children that older children tended to use linear representation more than younger children. However, even among 1st graders who were able to use linear representation in the estimation of numbers between 0 and 100, many switched to logarithmic representation when estimating numbers between 0 and 1000. These results provided support for the overlapping waves theory. More of such research is needed to firm up the cross-cultural applicability of the overlapping waves theory. This is the first main objective of the current research.