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Improving arithmetic performance with number sense training: An investigation of underlying mechanism

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ABSTRACT

A nonverbal primitive number sense allows approximate estimation and mental manipulations on numerical quantities without the use of numerical symbols. In a recent randomized controlled intervention study in adults, we demonstrated that repeated training on a non-symbolic approximate arithmetic task resulted in improved exact symbolic arithmetic performance, suggesting a causal relationship between the primitive number sense and arithmetic competence. Here, we investigate the potential mechanisms underlying this causal relationship. We constructed multiple training conditions designed to isolate distinct cognitive components of the approximate arithmetic task. We then assessed the effectiveness of these training conditions in improving exact symbolic arithmetic in adults. We found that training on approximate arithmetic, but not on numerical comparison, numerical matching, or visuo-spatial short-term memory, improves symbolic arithmetic performance. In addition, a second experiment revealed that our approximate arithmetic task does not require verbal encoding of number, ruling out an alternative explanation that participants use exact symbolic strategies during approximate arithmetic training. Based on these results, we propose that nonverbal numerical quantity manipulation is one key factor that drives the link between the primitive number sense and symbolic arithmetic competence. Future work should investigate whether training young children on approximate arithmetic tasks even before they solidify their symbolic number understanding is fruitful for improving readiness for math education.

1. Introduction

Humans are endowed with an intuitive understanding of number. Without counting or the use of symbols, we are able to estimate, compare, and mentally manipulate large numerical quantities (Feigenson, Dehaene, & Spelke, 2004). This nonverbal primitive number sense, termed the approximate number system (ANS), is shared by a diverse range of animal species (e.g., Merritt, DeWind, & Brannon, 2012) and is already present at birth in humans (e.g., Izard, Sann, Spelke, & Streri, 2009), which suggests that it is an evolutionarily ancient and developmentally rudimentary cognitive system (Brannon, 2006; Dehaene, 1999).

The ANS is characterized by imprecise noisy internal representations of number (Feigenson et al., 2004; Gallistel & Gelman, 2000). The signature of this system is that discrimination of number adheres to Weber's law—that is, the ability to discriminate two values depends on the ratio between the two values and not just their

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absolute difference. This characteristic allows us to estimate the precision of the internal representation of number by computing a Weber fraction (*w*) from data in which participants are asked to make simple non-symbolic numerical comparisons.

The ANS is hypothesized to be a core system and to be foundational for mathematical thinking in human adults (e.g., Feigenson et al., 2004). This hypothesis has been supported by recent studies that show a correlation between individual precision of the ANS, as measured by *w*, and individual mathematical competence as measured by standardized math tests, often even after controlling for verbal ability and general intelligence measures (DeWind & Brannon, 2012; Gilmore, McCarthy, & Spelke, 2010; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011; Libertus, Odic, & Halberda, 2012; Mazzocco, Feigenson, & Halberda, 2011a; Mazzocco, Feigenson, & Halberda, 2011b; Piazza et al., 2010). It should be noted, however, that many other studies now report negative findings (Castronovo & Gobel, 2012; Fuhs & McNeil, 2013; Gobel, Watson, Lervag, & Hulme, 2014; Holloway & Ansari, 2009; Inglis, Attridge, Batchelor, & Gilmore, 2011; Kolkman, Kroesbergen, & Leseman, 2013; Nosworthy, Bugden, Archibald, Evans, & Ansari, 2013; Price, Palmer, Battista, & Ansari, 2012; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Defever, Maertens, & Reynvoet, 2013; Sasanguie, Gobel, Moll, Smets, & Reynvoet, 2013; Tibber et al., 2013; Wei, Yuan, Chen, & Zhou, 2012), creating a controversy over whether the ANS is causally related to symbolic math and if so exactly what mechanisms underlie this relationship.

In a recent study (Park & Brannon, 2013), we tested the hypothesis that the ANS is causally related to math performance and found that training on a non-symbolic approximate arithmetic task leads to improvement in exact symbolic arithmetic. Participants who were trained to roughly add or subtract numerical quantities represented in dot arrays showed a significant improvement in a two- and three-digit arithmetic test. Although this previous study demonstrates that training with non-symbolic approximate arithmetic transfers to improvement in symbolic arithmetic, and provides strong evidence that the ANS may be directly and causally related to math ability, the study leaves open which cognitive component of the approximate arithmetic task was crucial for the obtained transfer effect. The non-symbolic approximate arithmetic task involves a number of different cognitive processes: estimation of numerical quantity from dot arrays, visual short-term memory required to hold numerical quantities and their sum or difference, and mental manipulation to combine or separate numerical quantities.

Here, in Experiment 1, we used a randomized controlled intervention approach to investigate the mechanisms that underlie the relationship between approximate arithmetic and exact symbolic arithmetic. We constructed multiple training conditions aimed at isolating and improving distinct cognitive components of the non-symbolic approximate arithmetic task. We then compared the transfer effects in exact symbolic arithmetic performance across these training conditions. In Experiment 2, a verbal interference approach was used to test the alternative hypothesis that the transfer effect observed in Park and Brannon (2013) and Experiment 1 of this report might be a function of undetected verbal encoding during approximate arithmetic.

2. Experiment 1

2.1. Material and methods

2.1.1. Participants

A total of 88 participants between 18 and 34 years of age participated in Experiment 1. Participants were recruited from the Duke University community and gave written informed consent in accordance with a Duke University Institutional Review Board approved protocol.

2.1.2. Procedure

Seventy-one participants were randomly assigned to four training groups in Experiment 1A: approximate arithmetic ($N = 18$, 7 males, age 21.5 ± 2.55 [mean ± s.d.]), approximate number comparison ($N = 18$, 7 males, age 21.9 ± 3.92), visuo-spatial short-term memory ($N = 18$, 8 males, age 21.4 ± 4.20), and numerical symbol ordering ($N = 17$, 6 males, age 21.5 ± 3.01). An additional 17 participants were recruited for Experiment 1B (9 male, age 21.1 ± 1.79). This group was trained with a task similar to the approximate arithmetic task but without the arithmetic component (henceforth referred to as approximate comparison and matching). See Section 2.1.3 for details about each training condition.

Upon enrollment, all participants were first given a pretest battery that consisted of an exact symbolic arithmetic test, vocabulary test, non-symbolic numerical comparison test, visuo-spatial 2-back test, and numeral order judgment test (see Section 2.1.4 for details). Participants in each training group were trained on six different sessions that took place within a two-week period. These training sessions were followed by a posttest session. The order of the pre- and posttests given was randomized. The average number of days between the first (pretest) and the last (posttest) sessions were 9.2 days (approximate arithmetic), 9.2 days (approximate number comparison), 9.3 days (visuo-spatial short-term memory), 9.1 days (numerical symbol ordering) and 9.0 days (Exp. 1B approximate comparison and matching) for each of the training groups.

2.1.2.1. Approximate arithmetic. The nonsymbolic approximate arithmetic training, identical to the condition used in Park and Brannon (2013), was used to replicate that study and to compare with other training conditions that were designed to isolate particular cognitive components of approximate arithmetic. Identical to the approximate arithmetic training condition used in Park and Brannon (2013), this training condition (Fig. 1A) required participants to add or subtract large quantities of visually presented dot arrays without counting. Participants were cued to mentally add or subtract two numerical quantities, ranging from 9 to 36, represented in dot arrays. Then, they were asked to either compare the sum or the difference