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Numerical processing efficiency improved in experienced mental abacus children

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ABSTRACT

Experienced mental abacus (MA) users are able to perform mental arithmetic calculations with unusual speed and accuracy. However, it remains unclear whether their extraordinary gains in mental arithmetic ability are accompanied by an improvement in numerical processing efficiency. To address this question, the present study, using a numerical Stroop paradigm, examined the numerical processing efficiency of experienced MA children, MA beginners and their respective peers. The results showed that experienced MA children were less influenced than their peers by physical size information when intentionally processing numerical magnitude information, but they were more influenced than their peers by numerical magnitude information when intentionally processing physical size information. By contrast, MA beginners and peers showed no differences in the reciprocal influences between the two conflicting dimensions. These findings indicate that substantial gains in numerical processing efficiency could be achieved through long-term intensive MA training. Implications for numerical magnitude representations and for training students with mathematical learning disabilities are discussed.

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1. Introduction

Humans are believed to share with non-human animals an evolutionarily ancient approximate number system (Dehaene, Dehaene-Lambertz, & Cohen, 1998; Gordon, 2004; Nieder & Miller, 2004; Xu & Spelke, 2000). However, what makes humans numerically unique is their acquisition of a symbolic number system that develops as early as preschool (Le Corre & Carey, 2007; Sarnecka & Carey, 2008), through childhood (Booth & Siegler, 2006; Siegler & Booth, 2004; Siegler, Thompson, & Opfer, 2009; Thompson & Opfer, 2010) and well into adulthood (Ansari, Garcia, Lucas, Hamon, & Dhital, 2005; Szucs, Soltesz, Jarmi, & Csepe, 2007). Dramatic improvements in the efficiency of using this symbolic number system occur as children gain experience with numerical symbols, especially after they begin to receive formal education (Ansari, 2008). When 3-year-olds from middle-income backgrounds or 4- and 5-year-olds from low-income backgrounds are asked to compare the numerical magnitude of two single-digit Arabic numerals, the performance of most children is near chance (Opfer & Siegler, 2012; Siegler & Ramani, 2008; Siegler & Robinson, 1982). By contrast, most first and second graders and even most kindergarteners are highly accurate on the comparison problems with single-digit or/and two-digit Arabic numerals (Laski & Siegler, 2007).

In addition to typical development and additional gains from formal school education, other mathematical activities such as number-related games (e.g. linear number board games) have also been found to be closely related to numerical development (Siegler & Ramani, 2008, 2009). It is popular, in China and other Asian countries, for children to learn mental abacus (MA) skills. A question worth exploring is whether MA users' improvements in mental arithmetic ability are accompanied by a

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corresponding advancement in their numerical processing abilities.

Children receiving MA training initially learn to perform calculations on a physical abacus, and they are later instructed to visualize such an abacus and move beads on this imaginary abacus with actual finger movements, as if they are manipulating real abacus beads. Eventually, children can manipulate numbers via an imaginary abacus without actual finger movements. Experienced MA users gain extraordinary abilities to solve mental arithmetic problems (even problems with large numbers of more than 10 digits) with unusual speed and accuracy (Hatano, Miyake, & Binks, 1977; Stigler, 1984).

Previous studies of MA primarily concern the processes and representations of MA calculation. Behavioral and imaging studies both suggest that MA users perform mental calculations nonlinguistically by drawing on visual and motor resources (Chen et al., 2006; Frank & Barner, 2011; Hanakawa, Honda, Okada, Fukuyama, & Shibasaki, 2003). Long-term MA training from an early age may even enhance the integrity of white matter tracts related to motor and visuospatial processes (Hu et al., 2011). However, no study, to our knowledge, has ever examined the relationship between MA training and numerical processing efficiency. According to some studies, the acquisition of MA skills not only improves calculation skills but also increases conceptual knowledge of the number system (Miller & Stigler, 1991; Stigler, Chalip, & Miller, 1986). Thus, a more abstract and flexible understanding of the number system might endow MA users with greater efficiency in processing numerical information.

Gains in the efficiency of manipulating this symbolic numerical system are hypothesized to reflect an enhanced association between numerical symbols and their corresponding numerical magnitudes. Two tasks frequently used to examine this numeral-magnitude association are the number line estimation task and the numerical magnitude comparison task. In the number line estimation task, participants are asked to place a target number on a number line that is empty except for the number 0 at the left end and a larger number (usually 10, 100 or 1000) at the right end. Number line estimation is a process of translating numerical symbols into internal numerical magnitude representations (Siegler & Booth, 2005). A logarithmic-to-linear shift in numerical magnitude representations, which is predictive of accuracy in the numeral-magnitude mapping, occurs both with long-term development and some short-term interventions (e.g. playing linear number board games) (Laski & Siegler, 2007; Siegler & Ramani, 2008). In the numerical magnitude comparison task, participants are asked to compare the numerical magnitude of pairs of numbers or make number comparisons with a fixed standard. Distance effect (the larger the numerical distance between the numbers, the better the performance) and size effect (the smaller the numerical magnitude of the numbers, the better the performance) obtained in this task are often viewed as markers of the noisy mapping from external symbolic representations of numerical magnitude onto internal analog representations (Holloway & Ansari, 2009). Distance effect and size effect generally decrease with age and experience (Duncan & McFarland, 1980).

However, the two types of tasks mentioned above can only examine the intentional processing of numerical information. The automatic processing of numerical information is also important because it provides a relatively uncontaminated picture of the internal representations of numerical magnitude (Fias & Fischer, 2005). Therefore, the full picture of numerical processing cannot be unveiled without a careful examination of both intentional and automatic processing of numerical information.

The numerical Stroop paradigm (NSP) is an ideal paradigm for examining the efficiency of access to numerical information both intentionally and automatically. In this paradigm, participants compare two simultaneously presented Arabic numerals either by their numerical magnitude or their physical size (see Table 1). In both the numerical magnitude comparison (NC) task and the physical size comparison (PC) task, adults and older children consistently exhibit typical congruity effects: they are faster and more accurate when comparing two numerals whose numerical magnitude and physical size are congruent (facilitation effect), and they are slower and less accurate when comparing two numerals whose numerical magnitude and physical size are incongruent (interference effect) (Girelli, Lucangeli, & Butterworth, 2000; Rousselle & Noël, 2008; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Szucs et al., 2007; Tzelgov, Meyer, & Henik, 1992). Congruity effects in NC are interpreted as the influence of the irrelevant physical size information, while congruity effects in PC are interpreted as the automatic activation of the irrelevant numerical magnitude information. The magnitude of these congruity effects can be considered to be a measure of numerical processing efficiency; smaller congruity effects in NC and larger congruity effects in PC correspond to greater numerical processing efficiency.

The present study aimed to explore the numerical processing efficiency of MA children. Our basic assumption was that children with great MA expertise gain a greater numerical processing efficiency than their peers without MA skills. MA expertise is acquired through long-term intensive training; thus MA learners with insufficient training should show few differences in numerical processing efficiency compared with their peers. The salience of the numerical information is found to increase gradually during childhood, although that of the perceptual dimension is already very high in infants and preschoolers (Feigenson, Carey, & Spelke, 2002; Mix, 1999; Rousselle & Noël, 2008; Rousselle, Palmers, & Noël, 2004). Therefore, gains in numerical processing efficiency in children with great MA expertise are possibly related to increased salience of the numerical information. To test our basic assumption and a number of specific hypotheses that flow

Table 1
Examples of numeral pairs used in the experiment.

	Congruent	Neutral	Incongruent
Numerical comparison task	3 8	3 8	3 8
Physical comparison task	3 8	3 3	3 8

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