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Long-term abacus training induces automatic processing of abacus numbers in children

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Abstract. Abacus-based mental calculation (AMC) is a unique strategy for arithmetic that is based on the mental abacus. AMC experts can solve calculation problems with extraordinarily fast speed and high accuracy. Previous studies have demonstrated that abacus experts showed superior performance and special neural correlates during numerical tasks. However, most of those studies focused on the perception and cognition of Arabic numbers. It remains unclear how the abacus numbers were perceived. By applying a similar enumeration Stroop task, in which participants are presented with a visual display containing two abacus numbers and asked to compare the numerosity of beads that consisted of the abacus number, in the present study we investigated the automatic processing of the numerical value of abacus numbers in abacus-trained children. The results demonstrated a significant congruity effect in the numerosity comparison task for abacus-trained children, in both reaction time and error rate analysis. These results suggested that the numerical value of abacus numbers was perceived automatically by the abacus-trained children after long-term training.

Keywords: abacus training, children, automatic, Stroop paradigm, congruity effect

1 Introduction

Abacus-based mental calculation (AMC) is a unique strategy for arithmetic that is based on the abacus (a traditional calculator), which has been used for thousands of years in East Asian countries (Menninger, 1969). With this specific mental calculation, AMC experts can solve calculation problems with extraordinarily fast speed and high accuracy (Hatano, Miyake, & Binks, 1977; Stigler, 1984). Experts acquire this capacity through a particular algorithm and long-term training (Hatano et al., 1977). Firstly, they learn to calculate with a real abacus (a simple device consisting of beads and rods, on which numbers can be represented by the spatial locations of beads), with both hands simultaneously. Then, after they are familiar with the operation of the abacus, they are instructed to imagine moving beads on an imagined abacus in their mind with actual finger movements. And, finally, they can calculate via the imagined abacus without moving their fingers, as if manipulating a 'mental abacus' (F. Chen et al., 2006; Frank & Barner, 2012; Hanakawa, Honda, Okada, Fukuyama, & Shibasaki, 2003; Hatano et al., 1977; Hishitani, 1990; Stigler, 1984).

Previous studies have demonstrated the superior performance of abacus experts on numerical tasks (Hatano et al., 1977; Stigler, 1984). Besides the extraordinary capability of mental calculations (especially on large numbers), abacus experts also have a much larger digit span than normal (Hatano & Osawa, 1983). Early behavioural studies suggested that these superior capabilities can be attributed to the employment of a mental abacus (Hatano & Osawa, 1983; Hatta, Hirose, Ikeda, & Fukuhara, 1989; Stigler, 1984), which indicated a visuospatial representation of numbers. For example, Hatano and his colleagues suggested that the digit memory of the abacus experts was disrupted more by concurrent visual–spatial tasks than by aural–verbal tasks (Hatano & Osawa, 1983). Similar results were found in another study: the performance in digit memory tasks for abacus experts was more affected

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by the presentation of the abacus figures than by the presentation of faces or digits, whereas the controls were more affected by the digits than faces or abacus pictures (Hatta et al., 1989). Numerous neuroimaging studies also found that nonverbal visuospatial cerebral networks were engaged during calculation tasks for abacus experts (C. L. Chen et al., 2006; F. Chen et al., 2006; Frank & Barner, 2012; Hanakawa et al., 2003; Ku, Hong, Zhou, Bodner, & Zhou, 2012; Tanaka et al., 2012; Wu et al., 2009). All these behavioural and neuroimaging studies suggested the existence of the mental abacus and the visuospatial representation of numbers.

However, most of those studies focus on the perception and cognition of Arabic numbers. It remains unclear how the numbers represented by an abacus schematic (named 'abacus numbers' in the present study) were perceived. Since the abacus expert processes numerical information by manipulating the mental abacus directly, the study of the mechanism for processing abacus numbers for abacus users is of great significance.

A large number of studies have revealed that numerical processing (both symbolic and nonsymbolic) is automatic (Henik & Tzelgov, 1982; Rubinsten & Henik, 2005; Szűcs & Soltész, 2007), which means that this process begins immediately and involuntarily upon seeing numbers. Besides, it is well known that automaticity can be attained after repeatedly performing the same task for a long period of time (ie long-term training) (Schneider & Shiffrin, 1977). For the present study, as AMC is a skill that requires a long period of practice, we assumed that the perception of the numerical value of abacus numbers was automatic for the abacus-trained Chinese children.

Generally, automaticity is studied by using a conflict strategy such as the Stroop task (Cohen Kadosh, Soskic, Iuculano, Kanai, & Walsh, 2010; Stroop, 1935). In this classical paradigm participants are presented with a two-dimensional stimulus (colour words—for example, the word GREEN in a blue colour) and are asked to name the colour of the ink (ie blue) and ignore the meaning of the word (ie GREEN). Generally, participants cannot ignore the irrelevant dimension (the meaning of the word), which interferes with the processing of the relevant one (the colour of the ink). Such a result is considered as an indication of automatic processing of the irrelevant dimension. The numerical Stroop paradigm (NSP) is a modified form of the classic colour-word Stroop paradigm. It is often employed to investigate the automaticity of the processing of numerical information (Henik & Tzelgov, 1982). In the task participants are presented with two Arabic digits and asked to decide which one has the larger physical size (ignoring the irrelevant numerical value). Results show that the irrelevant numerical value can interfere with the processing of the relevant physical size of the digit, indicating that the perception of Arabic digits is an automatic process (Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Rubinsten & Henik, 2005; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). The NSP has also been used to measure numerical automatic processes in the developmental dyscalculia population (Furman & Rubinsten, 2012; Rubinsten & Henik, 2006; Soltész, Szűcs, Dékány, Márkus, & Csépe, 2007).

In the present study, in order to explore the automaticity of processing of the numerical value of abacus numbers for abacus-trained children, Arabic numbers are substituted by abacus numbers (numbers represented by abacus schematics; see figure 1a). These abacus numbers also have two dimensions of meaning. One is the numerical value of the abacus number, and the other is the numerosity of beads that constitute the abacus number. Since the reaction time (RT) of counting (more than four items) increases notably with the number of items (about 250 ms per item) (Balakrishnan & Ashby, 1991, 1992; Piazza, Mechelli, Butterworth, & Price, 2002), the maximum number of beads for all abacus numbers in this study is restricted to 4. Thus, the perception of the numerosity of abacus beads is confined to the domain of subitizing (Kaufman, Lord, Reese, & Volkmann, 1949; Trick & Pylyshyn, 1993)—which is a fast, automatic, and accurate evaluation of a small set of objects (typically, 1 to 4 items), and the RT increases slightly with the number of items (about 50 ms per item).

Previous studies concerned with the congruity effect between subitizing and numerical values were carried out by employing the enumeration Stroop task (Naparstek & Henik, 2010; Pavese & Umiltà, 1998, 1999). In this task participants are presented with a visual display containing a number of items (Arabic numbers) and asked to report the numerosity of items while ignoring their identity or to report the identity of the presented items while ignoring their numerosity. Results indicate that irrelevant numerical values modulated performance regardless of task (Naparstek & Henik, 2010).

For the present study a similar enumeration Stroop task is employed, in which participants are presented with a visual display containing two abacus numbers and asked to compare the numerosity of beads that consisted of the abacus number. We hypothesize that the irrelevant numerical value of the abacus numbers will modulate the performance in the numerosity comparison task.

2 Methods

2.1 *Participants*

Two groups of children participated in the study. One was the abacus-trained group, including twenty-nine children (age = 10.53 ± 0.41 years; range: 9.67–11.34 years; fourteen girls, fifteen boys); and the other was the nontrained group, including twenty-eight age-matched and education-matched normal children (age = 10.56 ± 0.33 years; range: 10.01–11.26 years; fourteen girls, fourteen boys). These children were recruited from different classes of the same grade of an elementary school, in Weifang City, China. At the beginning of their schooling all children were randomly assigned into two experimental groups. After grouping, no children applied to change their group or stop participation. The abacus-trained children had been practising abacus operation and AMC for 2 to 3 h per week for approximately 3 years (the combined practices of abacus operation and AMC were named as 'abacus training' in this study). In contrast, the nontrained group received no abacus training either at school or after school. Except for the abacus training, all children studied the same curriculum at school.

All participants were right-handed children with normal or corrected-to-normal vision, and reported no history of neurological problems. Informed consent was obtained from both the child and his or her parents after a complete description of the study. Our study was approved by Zhejiang University.

2.2 *Stimuli and task*

Stimuli were pairs of abacus numbers. Each abacus number was represented by one abacus schematic. These abacus numbers ranged from two to seven. Each schematic can be perceived in two ways: by calculating the numerical value of the abacus schematic or by enumerating the numerosity of abacus beads. Thus the stimuli varied along two dimensions: one was the numerical magnitude, and the other was the numerosity of beads consisting of the abacus number. The abacus bead pairs were presented in two different levels of congruity: congruent and incongruent. In the congruent condition the side of the larger numerical value that the abacus beads represented coincided with the side which contained a greater number of beads (larger numerosity). However, in the incongruent condition the side of the larger numerical value that the abacus beads represented coincided with the side which contained a smaller number of beads (smaller numerosity). As there were not enough neutral abacus bead pairs, the neutral condition was omitted in the study (only two pairs: 2–6 and 3–7, which had the same numerosity of beads but different value).

As shown in table 1, there was a total of 12 different congruent number pairs and incongruent number pairs (six pairs for each condition). Each pair appeared 16 times in the experiment, 8 times in ascending order (eg 2–3) and 8 times in descending order (eg 3–2). Figure 1a shows the Arabic digits corresponding to the abacus bead schematics.

Table 1. Digit pairs according to the two conditions (congruent and incongruent).

Condition	Bead pairs	Condition	Bead pairs
Congruent	2–3	Incongruent	2–5
	2–4		3–5
	3–4		3–6
	5–6		4–5
	5–7		4–6
	6–7		4–7

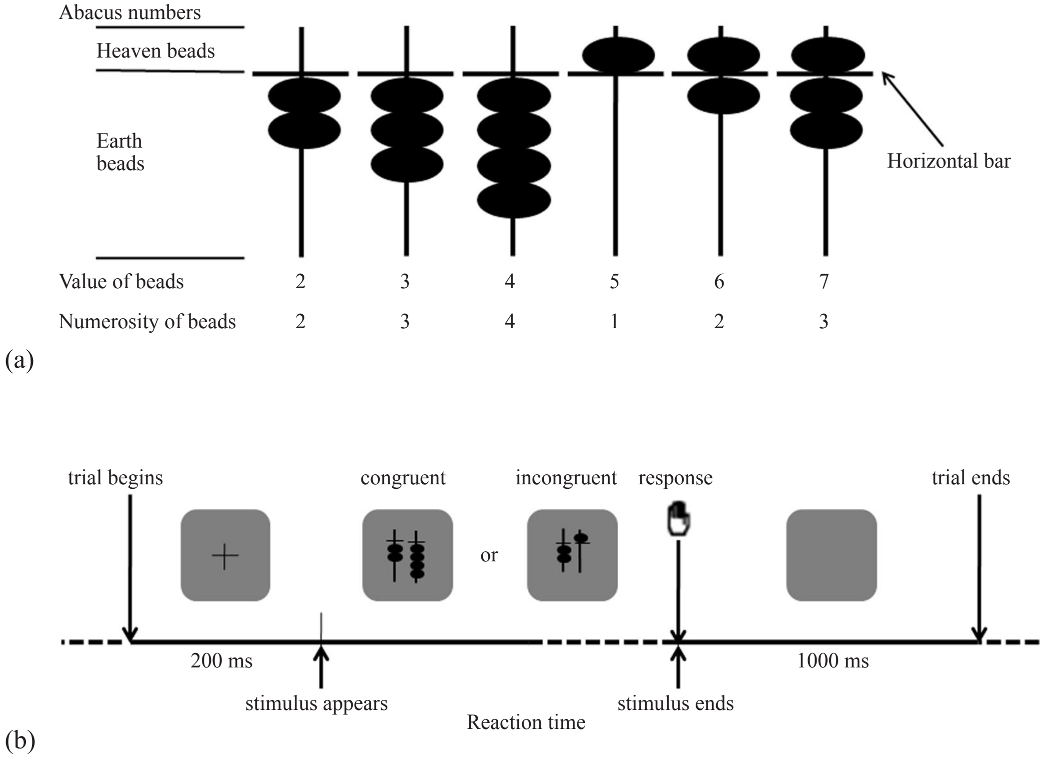

Figure 1. (a) The two dimensions of the beads. A bead above the horizontal bar (named as a heaven bead) equals five and a bead below (named as an earth bead) equals one. Thus, the value of an abacus number = the numerosity of the earth bead + 5 × the numerosity of the earth bead (0 or 1). (b) The procedure of a trial. Each trial started with the presentation of a fixation of 200 ms, followed by the presentation of a bead pair until response, and ended with a blank (grey screen) of 1000 ms.

The viewing distance was approximately 50 cm from the centre of the screen, such that stimuli subtended a visual angle of 6.70 deg and 2.33 deg in length and width, respectively, for each abacus bead.

Two experimental tasks were involved in the study: the numerosity of beads comparison task and the value of beads comparison task. In the numerosity comparison task subjects were instructed to decide which item of the pair had a greater number of beads than the other. In the value comparison task subjects were instructed to decide which item of the pair was numerically larger than the other. Subjects were asked to make their decisions by pressing a response button on the side (left or right) where they detected the right answer. The abacus-trained children executed both of the two tasks. However, only the result of the numerosity comparison task was taken into account for the nontrained children, as they did not receive any abacus training.

All experimental tasks were carried out on a PC using E-prime v1.1 (Psychology Software Tools Inc., Pittsburgh, PA; http://www.pstnet.com/prime). RT and accuracy were recorded by the PC.

2.3 *Experimental procedure*

Abacus number pairs were presented in a pseudorandom order (the same pair never appeared in two consecutive trials). Each trial started with the presentation of a fixation of 200 ms, followed by the presentation of a bead pair until response, and ended with a blank (grey screen) of 1000 ms (see figure 1b). For abacus-trained children the whole experiment was divided into four blocks (2 blocks for each task, 48 trials for each block), and a short break was allowed between blocks. The sequence of the two tasks was counterbalanced within the four blocks. Children completed 48 practice trials (24 for each task) before the formal test to ensure task comprehension and response assignment. For nontrained children only two blocks of the numerosity comparison task were executed, and 24 practice trials before the formal test were carried out. Data from practice trials are not reported in the analysis. Instructions emphasized both speed and accuracy.

3 Results

Three participants were excluded due to their misunderstanding of the comparison task (one abacus-trained child and two nontrained children; the accuracy rate was lower than 55% in one task). The means of median RTs and error rates for each experimental condition are shown in table 2.

Table 2. Means of median reaction times (RTs) and error rates as a function of task and congruency in the abacus-trained and nontrained groups.

		Numerosity comparison		Value comparison	
		RT/ms	% error	RT/ms	% error
Abacus-trained group	congruent	777 (178)	0.6 (1.4)	839 (160)	4.1 (4.8)
	incongruent	886 (280)	8.6 (12.1)	810 (179)	8.1 (11.9)
Nontrained group	congruent	590 (91)	0.6 (1.4)		
	incongruent	581 (100)	1.4 (1.5)		

Note: Standard deviations for latencies and error rates are in parentheses.

3.1 *The numerosity of beads comparison task*

RT analysis: The median RTs were calculated for each participant in each condition for correct trials only. These correct median RTs were subjected as a dependent variable to an ANOVA with congruity condition (congruent and incongruent) as a within-subjects factor and group (the abacus-trained group and the nontrained group) as a between-subjects factor in each comparison task. Differences of the median RTs and error rates between the two congruity conditions for the two groups are shown in figure 2.

A main effect of group was significant ($F_{1,52} = 26.74$, $p < 0.01$, $\eta_\text{p}^2 = 0.34$), showing that the response time of the abacus-trained group was significantly longer than the nontrained group (832 ± 239 ms and 586 ± 95 ms for the abacus-trained and nontrained group, respectively). A main effect of congruity was also highly significant ($F_{1,52} = 13.47$, $p = 0.01$, $\eta_\text{p}^2 = 0.21$); it revealed that incongruent pairs were processed significantly slower than congruent pairs (687 ± 170 ms and 739 ± 262 ms for the congruent and incongruent conditions, respectively). More importantly, the interaction between group and congruity was also significant ($F_{1,52} = 18.80$, $p < 0.01$, $\eta_\text{p}^2 = 0.27$). Decomposition into contrasts showed that there was a congruity effect in the abacus-trained group ($t = -4.28$, df = 27,

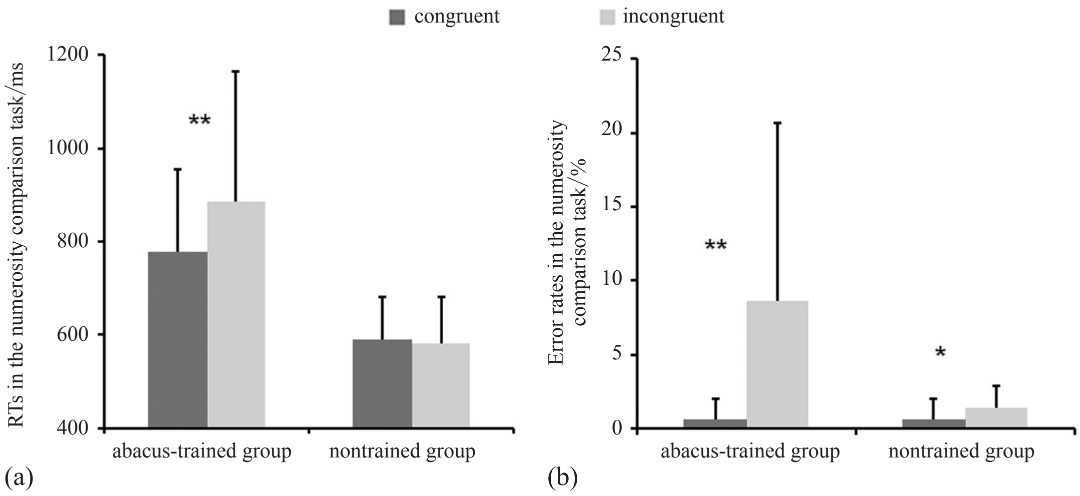

Figure 2. Means of median RTs and error rates as a function of congruity level (congruent or incongruent) for the abacus-trained and nontrained groups in the numerosity comparison task. (a) The differences of the median RTs; (b) the differences of the error rates. * $p < 0.05$; ** $p < 0.01$.

$p < 0.01$, Cohen's $d = -0.46$, 777 ± 178 ms and 886 ± 280 ms for the congruent and incongruent conditions, respectively), but not in the nontrained group ($t = 1.31$, df = 25, $p = 0.20$, Cohen's $d = 0.09$, 590 ± 92 ms and 581 ± 100 ms for the congruent and incongruent conditions, respectively).

Error rate analysis: The overall error rate was 3.1%. The error rate for each subject in each condition was calculated and submitted to an ANOVA with congruity (congruent and incongruent) as a within-subjects factor and group (abacus-trained and nontrained group) as a between-subjects factor.

A main effect of group was significant ($F_{1,52} = 8.46$, $p < 0.01$, $\eta_p^2 = 0.14$), showing that the abacus-trained children made more mistakes than the nontrained children (4.6% ± 9.4% and 1.0% ± 1.5% for the abacus-trained and nontrained children, respectively). A main effect of congruity was also highly significant ($F_{1,52} = 13.66$, $p < 0.01$, $\eta_p^2 = 0.21$); it revealed that the error rate for incongruent pairs was significantly larger than congruent pairs (5.2% ± 9.4% and 0.6% ± 9.4% for the incongruent and congruent conditions, respectively). In line with the RT analysis, there was also an interaction between group and congruity ($F_{1,52} = 9.14$, $p < 0.01$, $\eta_p^2 = 0.15$). Decomposition into contrasts showed a significant congruity effect in the abacus-trained group ($t = -3.53$, df = 27, $p < 0.01$, Cohen's $d = -0.93$, 8.6% ± 12.1% and 0.6% ± 1.4% for the incongruent and congruent conditions, respectively), and also in the nontrained group ($t = -2.08$, df = 25, $p = 0.048$, Cohen's $d = -0.54$, 1.4% ± 1.5% and 0.6% ± 1.4% for the incongruent and congruent conditions, respectively). Compared with the abacus-trained group, the congruity effect (incongruent vs congruent) was smaller in the nontrained group ($t = 2.60$, df = 52, $p = 0.01$, Cohen's $d = 0.72$).

The significant group effects in both of the RT and error analysis indicated that the task is more difficult for the abacus-trained children. Although both groups showed congruity effects in the error rate analysis, the effect size was smaller in the nontrained group. In the RT analysis the effect existed in only the abacus-trained group.

3.2 *The value of beads comparison task*

The overall error rate was 6.3%. The median RTs (only for correct trials) and mean error rates were calculated for each participant in each condition. These median RTs and error rates of the two conditions (congruent and incongruent) were subjected to a paired *t*-test. Only the data for the abacus-trained group were considered here. The result showed that no significant difference was detected between the two conditions in either the RT analysis ($t = 1.58$, $\mathrm{df} = 27$, $p > 0.05$) or the error rate analysis ($t = 1.68$, $\mathrm{df} = 27$, $p > 0.05$).

4 Discussion

The purpose of the current study was to investigate the automatic numerical processing of abacus numbers in abacus-trained children. To address this issue, we adopted a modified enumeration Stroop paradigm (according to the special particularities of abacus bead numbers) and explored the congruity effect of the irrelevant numerical value of the abacus numbers. To the best of our knowledge, this is the first report revealing the effect of long-term training on automatic processing of abacus numbers.

The result confirmed our hypothesis. We found a significant congruity effect in the numerosity comparison task for abacus-trained children, in both the RT and error rate analysis. This congruity effect was similar to the size congruity effect revealed by previous studies that focused on the Arabic number system. The size congruity effect has been considered for almost 20 years as a marker of automatic numerical processing (Gebuis, Kadosh, de Haan, & Henik, 2009; Henik & Tzelgov, 1982; Kadosh, Bien, & Sack, 2012; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Szűcs & Soltész, 2007; Tzelgov, Meyer, & Henik, 1992). Similar results were also found in the enumeration Stroop tasks. For example, in a study which used the enumeration Stroop task (Naparstek & Henik, 2010), subjects were presented with displays containing a variable number of digits and were asked to pay attention to the number of digits or to their numerical value. Two kinds of tasks were provided to subjects, including a comparative judgment task and a parity judgment task. They found that irrelevant numerical values modulated performance regardless of task, and suggested that the numerical value is activated automatically. Thus, the congruity effect in our study also suggested the automatic processing of the numerical value of abacus numbers for abacus-trained children.

In nontrained children, although there was a congruity effect in the error rate analysis, no statistical difference was found between the congruent and incongruent tasks in the RT analysis. Further, the error rate congruity effect in the nontrained children was smaller than that in the abacus-trained children. The result showed that abacus-trained children were more affected by the irrelevant numerical value of the abacus numbers than nontrained children when performing the numerosity comparison task. First of all, this result suggested that the processing of irrelevant numerical values of abacus numbers for abacus-trained children was more automatic than in the nontrained children, according to the previous numerical-automaticity-related studies, in which the greater level of automaticity was reflected by a larger size congruity effect (Girelli et al., 2000; Kadosh et al., 2012; Rubinsten & Henik, 2005, 2006; Wang, Geng, Hu, Du, & Chen, 2013). Our result also suggested that automatic processing of irrelevant numerical values of abacus numbers in abacus-trained children may be derived from long-term training. This was consistent with the conception that sufficient training can induce skilled and automatic performance in various cognitive tasks (Cohen Kadosh et al., 2010; Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004; Schneider & Shiffrin, 1977; Tzelgov, Yehene, Kotler, & Alon, 2000). Lastly, one may ask why there was an error rate congruity effect in the nontrained group, as nontrained children were supposed to be isolated from the abacus course, and the irrelevant numerical value of abacus numbers should not be processed in the numerosity comparison task. We thought that what accounted for this phenomenon was that some of the nontrained children might master the algorithm of the abacus schematic, although they received no abacus training either at school or after school. They might obtain the knowledge of abacuses from their parents, because it is such a simple tool and it is easy to read the value of an abacus number (most Chinese adults have the ability to read values even if they cannot calculate with the tool).

However, one may notice that the average distance between items in the numerosity comparison task is 1.33 and 1.67 for the congruent and incongruent condition, respectively (the distance was 1 for the abacus number pairs 2 vs 3, 3 vs 4, 5 vs 6 in the congruent condition and 6 vs 7, 2 vs 5, 3 vs 6, 4 vs 7 in the incongruent condition; the distance was 2 for the abacus number pairs 2 vs 4 and 5 vs 7 in the congruent condition and 3 vs 5 and 4 vs 6 in the incongruent condition; the distance was 3 for the abacus number pair 4 vs 5 in only the incongruent condition). According to Moyer and Landauer (1967), this dissociation of the average distance between two congruity conditions should lead to a numerical distance effect: the time taken to judge the greater of two numerals is an inverse function of the numerical difference ('symbolic distance') between the items. This effect was found in all numerical judgments (Dehaene, 1997; Girelli et al., 2000) and can be explained by the 'mental number line' (Dehaene, 1997; Dehaene, Dupoux, & Mehler, 1990). In the present study, though, the RTs of the congruent condition (the average distance is 1.33) were smaller than the incongruent condition (the average distance is 1.67), which seems like a reverse distance effect. In order to explain this phenomenon, the distance effects in each condition for both groups were examined in part 1 of the supplementary material (http://www.perceptionweb.com/perception/misc/p7625/p7625-Supplement.pdf). Results showed classic distance effects in each congruity condition for both groups (*p*s < 0.05). These distance effects were consistent with previous studies (Dehaene, 1997; Girelli et al., 2000; Moyer & Landauer, 1967). Besides this, we reported part of the behavioural results from another event-related potentials (ERP) study (unpublished) in our laboratory with two groups of children (part of the participants attended both the ERP study and the current behavioural experiment) in part 2 of the supplementary material. In the digit comparison task of the ERP study, children were shown an Arabic digit number (1, 4, 6, or 9), and were asked to compare the stimulus with a standard number 5. Results showed classic distance effects in each group of children (*p*s < 0.05). These results support the idea that the distance effect of the abacus-trained children is in line with the nontrained children, as well as the classic distance effect in previous studies (Dehaene, 1997; Girelli et al., 2000; Moyer & Landauer, 1967). The distance effects of abacus-trained children in both the numerosity comparison task of the present study and the Arabic number task were similar and classic, indicating that the representation of numerical magnitudes for abacus-trained children was consistent with the nontrained children. Thus, the performance of RTs (the congruity effect) in two congruity conditions strongly suggested automatic processing of the numerical value of abacus numbers for abacus-trained children.

In the value comparison task abacus-trained children showed no congruity effects, so we cannot make the conclusion that perceiving the numerosity of abacus beads (which is supposed to be a kind of subitizing which can be automatically perceived) was automatic. This was dissociated from a previous study (Naparstek & Henik, 2010) as mentioned in the introduction, which showed that irrelevant numerosities modulated performance in the numerical comparative judgment task. In their study participants were asked to indicate whether the numerosity or the numerical value of the digits was smaller or larger than 5. Our task was similar to their study, whereas the irrelevant numerosities did not modulate the performance in the numerical comparison task. Why? We think this may be due to the fact that intensive long-term abacus training has changed the brain structure (Hu et al., 2011; Li, Wang, Hu, Liang, & Chen, 2013), neural function (F. Chen et al., 2006; Wu et al., 2009), and the number processing system (Wang et al., 2013). These changes may make perceiving the numerical value of abacus numbers a much greater priority than perceiving the numerosity of abacus numbers. Thus, they might cognize the numerical value of abacus numbers whenever it is relevant. In addition, there was no control group in the numerical value comparison test, as the nontrained children cannot execute the task. Thus, we only discussed this result here and did not treat it as a conclusion.

However, there were limitations in the present study. The value comparison task was not suitable for the nontrained children, although this was not fatal for the present study. Furthermore, only one group of abacus-trained children was recruited in our study; children with different training intensities should be involved in future studies.

Nonetheless, our results still indicate that the numerical value of abacus numbers is perceived automatically after long-term training. Additionally, the present study might be helpful for children who have difficulty dealing with numbers (eg children with developmental dyscalculia), as abacus training can construct a novel symbolic system of numerical cognition.

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