Trends in Neuroscience and Education 2 (2013) 13–22

Contents lists available at SciVerse ScienceDirect

Trends in Neuroscience and Education

journal homepage: www.elsevier.com/locate/tine

Does math education modify the approximate number system? A comparison of schooled and unschooled adults

Julie Nys [a,*], Paulo Ventura [b], Tania Fernandes [b,1], Luis Querido [b], Jacqueline Leybaert [a], Alain Content [a]

[a] Laboratoire Cognition, Langage et Développement (LCLD), Centre de Recherche Cognition & Neurosciences (CRCN), Université Libre de Bruxelles (ULB), 50/CP 191 Av. F. Roosevelt, B-1050 Brussels, Belgium

[b] Faculdade de Psicologia e de Ciências da Educação, Universidade de Lisboa, Alameda da Universidade, 1649-013 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 25 April 2012
Accepted 21 January 2013

Keywords:
Approximate number system
Education
Magnitude
Mathematics
Schooling

ABSTRACT

Does math education contribute to refine the phylogenetically inherited capacity to approximately process large numbers? The question was examined in Western adults with different levels of math education. *Unschooled* adults who never received math education were compared to *unschooled-instructed* adults who did not attend regular school but received math education in adulthood, and to *schooled* adults who attended regular school in childhood. In the number-comparison task (Exp. 1), the unschooled group was slower and made more errors than the other groups both when numerical symbols and nonsymbolic dot collections were presented. In the forced-choice mapping task (Exp. 2), the unschooled group experienced more difficulty than the others in linking large nonsymbolic and symbolic quantities, as well as in matching purely nonsymbolic quantities. These results suggest that Western adults who did not receive math education have less precise approximate number skills than adults who acquired exact number competences through math education.

1. Introduction

To what extent can biologically-determined cognitive skills be modified by cultural inventions? Numerical capacities constitute a good candidate to examine this question since their development involves both biological and cultural determinants. Indeed, it is often assumed that number skills are built upon a primitive approximate number system shared phylogenetically and that they are also driven by the acquisition of numerical notations and by mathematical education [7]. Here, we examined through behavioral techniques whether the formal acquisition of math skills is capable of modifying preexistent cognitive number abilities. Schooled and unschooled adults who benefited from different types of education were compared on large number apprehension tasks to assess whether math education affects the development of the inherited capacity to approximately process number magnitude.

Current conceptions about the development of number abilities assume that humans possess a core number system which enables them to approximately perceive or compare quantities and constitutes the foundation of later exact number skills (e.g., [7,45]). For instance, newborns already appear sensitive to numerical congruency between visual and auditory stimuli [23], demonstrating a rudimentary ability to capture numerical properties abstracted from sensory information. Habituation studies have also demonstrated that 6-month-old infants are able to discriminate between collections of dots on the basis of number, at least as long as the numerical distance or numerical ratio is sufficiently large (e.g., 2:1 ratio such as 16 vs. 8 dots, or 24 vs. 12 dots, see [4,49,51,52]), suggesting that their representation of number is still of limited precision. The observation that performance in number discrimination can be predicted by the numerical ratio in human infants as well as in other species (e.g., see [8] for a review) supports the view that humans and non-human animals share an approximate number system, which is the product of biological evolution, emerges independently of language or of mathematical education [11,51], and endows them with the ability to encode the numerosity of environmental objects or events in such a way that its precision decreases in proportion to number magnitude.

Even though human infants may come to the world equipped with perceptual mechanisms enabling them to approximately apprehend number magnitude, the precision of the approximate number system evolves across the life span, as reflected by the fact that accuracy in nonsymbolic number comparison tasks increases with age. This developmental trend has been established both during infancy [26,48,50] as well as in later childhood [19,41]. For instance, Halberda and Feigenson [19] demonstrated that adults can detect smaller numerical differences between sets of dots than 5-year-old children, suggesting that the acuity of the approximate number system increases between childhood and

* Corresponding author. Tel.: +32 2 650 4581; fax: +32 2 650 2209.
E-mail address: julienys@ulb.ac.be (J. Nys).

[1] Present address: Lab. de Fala, Universidade do Porto, Portugal.

2211-9493/$ - see front matter
http://dx.doi.org/10.1016/j.tine.2013.01.001

adulthood. In a recent review, Piazza [40] similarly reported that young adults would be able to perceive arrays contrasting by an 8:7 ratio as different, whereas the performance of 5-year-olds would be limited to ratios 5:4 or above.

Several authors have suggested that such developmental changes could be due to maturational processes, but some have also envisaged the possibility that the improvement might be influenced by formal mathematics education and school activities such as counting or arithmetic [19,20,34,41]. Until recently, the two hypotheses regarding the processing of large numbers have not been tested directly, and unfortunately they cannot be disentangled on the sole basis of the aforementioned past studies because when children are assessed at different ages or compared to adults, maturation and schooling effects are confounded. However, one piece of evidence in favor of the idea that the human capacity to approximately process large numbers might be partly shaped by the formal acquisition of number symbols and of exact numerical knowledge comes from research on indigenous populations, such as the Piraha [13,17] or the Mundurukù [43]. Piraha and Mundurukù are Amazonian populations who have received little or no schooling experience and whose language for numbers is very limited. For instance, the Mundurukù have words for representing small quantities ranging from one to five and very rough quantifiers, such as the equivalent of "some" or "many", for larger quantities. Pica and colleagues showed that the Mundurukù have developed approximate number abilities despite their limited number–word lexicon. Indeed, they are able to compare large sets of dots and decide which set is numerically the biggest, demonstrating that they can spontaneously extract numerosities from large sets of dots. According to the authors, this finding provides evidence that the approximate number abilities constitute a fundamental competence, arising independently of language and of instruction. However, closer analysis of the data indicates that the Mundurukù's approximate number skills were less accurate than those of the French participants. Indeed, in the dot number comparison task, the Mundurukù were slower than the French controls and failed to discriminate numerical differences as slight as those detected by the controls. Because it cannot be explained by maturational processes, we believe that the observation of such group differences might be taken as evidence for the hypothesis that mathematical education influences the development of the capacity to approximately process number magnitude.

However, besides the fact that the Mundurukù do not steadily receive education in mathematics, other cultural factors might also be at play. Actually, the use of number is very restricted in their culture: in addition to having an extremely limited number–word lexicon, the Mundurukù also use verbal numerals most of the time in an approximate manner only, they do not use counting spontaneously or correctly, and they usually do not practice monetary exchange which could provide experience with numbers (see [43], Supporting Online Information). For these reasons, it remains unclear whether the particular pattern of performance observed in this population results either from their non-Western and non-numerically based culture or from the lack of mathematical education itself.

Therefore, investigating the number skills of people who are living in a Western cultural context but who did not benefit from education in mathematics would be a suitable approach to address more directly the impact of math education on approximate number processing. In a study aimed at standardizing and validating their number processing test battery, Deloche and colleagues [10] assessed a wide range of basic numerical skills in healthy Western illiterate and semi-literate adults. The data indicated large inter-individual differences and revealed that illiterate Western adults are not completely devoid of verbal counting skills, knowledge of Arabic numerals and calculation procedures. In other words, despite the lack of formal education in mathematics, Western illiterates are not completely "innumerate", which contrasts with their inability to read even isolated letters or to deal with phonemic segmentation [29,30].

In a very recent study, Zebian and Ansari [53] went a step further by assessing the elementary ability to process small quantities ranging from one to nine in minimally literate and highly literate Syrian adults. Minimally literate participants had received no more than one year of schooling and they were able to read single-digit Arabic numerals but not words, while highly literate participants had attended school for more than 10 years and had no reading difficulties. Whereas minimally literate participants showed a steeper effect of numerical distance when asked to compare single digits, no group difference was observed in the ability to compare the corresponding nonsymbolic numerosities. Although the authors acknowledged that the strategies used to compare nonsymbolic stimuli numerically could differ according to the level of literacy and education, they interpreted these results as showing that the capacity to process nonsymbolic numerical magnitude is not affected by enculturation. However, because the processing of small numbers could differ from that of larger numbers (e.g., [15,16,35]), drawing such a general conclusion on the sole basis of results implying small numerical quantities only may seem premature. Examining whether schooling and math education shape the ability to process large numerical magnitudes was the aim of the current study.

Two experiments designed to assess approximate number skills with large numbers were administered. In *Experiment 1*, the participants received a classic number comparison task, in which they had to judge which of two quantities was the numerically largest one. The numerical ratio was manipulated in order to assess whether performance showed the signature of the approximate number system. Two formats of presentation were used. In Exp. 1A, the participants had to compare sets of dots in order to assess their core approximate number skills. In Exp. 1B, they were asked to compare two-digit Arabic numbers in order to evaluate their access to number magnitude from numerical symbols. In *Experiment 2*, the participants received a Forced Choice Mapping Task, in which they had to choose among three quantities the one that numerically matched a target-quantity previously presented. The numerical distance between the target and the choice-quantities was varied so that trials included difficult items (close distractors) as well as easier items (distant distractors). Two formats of presentation were used. In the nonsymbolic (NS) mapping condition, the target and the choice-quantities were all nonsymbolic. In the NS/S mapping condition, the target was nonsymbolic whereas the choice-quantities were symbolic or vice versa.

The tasks were administered to three groups of adult participants, living in Portugal, who had benefited from different types and levels of education: *unschooled* participants, who had never received education in mathematics, were compared to *unschooled-instructed* participants, who had never attended regular school but had received non-formal education in mathematics during adulthood, and to *schooled* participants who had attended regular school during childhood. The comparison of these three populations offers several advantages. First, because the three groups are composed of participants of the same age, the observation of group differences cannot be attributed to maturation, thus contrasting with studies based on the comparison of preschoolers and older children or adults. Second, the effects cannot be ascribed to the cultural environment in which they live or to differences in the cultural prominence of number, because all three groups share an identical Western cultural context. Third, the comparison of unschooled-instructed participants to schooled participants helps to distinguish between the impact of formal schooling and the effect of mathematical education. As a consequence, clear-cut predictions can be made. If the capacity to process number magnitude follows age-related mechanisms but develops independently of schooling and of mathematical learning, performance should be equivalent in the three groups of participants. By contrast, if mathematical education enhances the precision of the approximate number skills, the unschooled group should demonstrate poorer performance than the other two groups. Finally, if formal schooling itself is a key determinant of number skills, performance should be poorer in the unschooled group and in the unschooled-instructed group than in the schooled group.

2. Experiment 1

2.1. Method

2.1.1. Participants

In the current study, we looked for the potential effect of education on performance in approximate number tasks. Thus, three groups of adult participants, who live in a similar Western cultural context but who had received different types and levels of education, were tested in Portugal: 14 participants had never attended school (Unschooled group), 15 had never attended regular school during childhood but had received reading, writing and math education during alphabetization classes for adults (Unschooled-instructed group), and 15 participants had received standard school education during childhood (Schooled group). Participants from the unschooled-instructed group had attended literacy and numeracy courses for approximately 4 years (SD = 1.7)[2], during five days a week, and for three hours per day. The courses that those participants received put emphasis on problems they were experiencing in their everyday life, and were thus directly related to their professional occupation. As most of these participants were involved in trade during their work (implying sales activities and practice of mental calculation because of money exchange), emphasis was put on mathematics during the courses, especially on numerical symbols learning and on exact arithmetic. Participants from the schooled group benefited on average from approximately 8 years of formal education (SD = 3.4) during childhood.

The validity of the group assignment was further assessed through the administration of a reading test. Indeed, literacy has been used as a proxy for education in many other studies (e.g., [24,39,53]), and reading tests seem thus appropriate to check for the level of education that the participants reported to have received. The participants from the unschooled group were expected not to be able to read, in contrast to the participants from the two other groups. The evaluation of reading included a letter identification task, a reading test including six words and six pseudowords, and a reading test including sentences ([27], adapted for Portuguese). One female participant was excluded from the initial sample of unschooled participants because, though unable to read any sentence, she could read 3 words and 2 pseudowords among the 12 items from the reading test. All other participants from the unschooled group were unable to read any item from the reading test. Participants from the unschooled-instructed group read at least 75% of the stimuli from the reading test. Participants from the schooled group experienced no difficulty in the reading tests.

All participants also performed the Mini-Mental State Examination (MMSE) in order to guarantee that none of them had any cognitive impairment ([12]; adapted for portuguese, see [18]). The MMSE assesses time and space orientation, immediate and delayed verbal memory, attention and calculation, language and visuo-constructive abilities. The MMSE leads to a maximum total score of 30. Since performance on specific MMSE items has been shown to be influenced by education (e.g., [1,3,38]), previous studies used different cut-off scores according to the educational level to differentiate individuals with intact cognitive functioning from patients with dementia. Specifically, based on the validated Portuguese adaptation of the MMSE [18], cut-off points of 15, 22 and 27 were used in the present study for unschooled participants, participants with 1–11 years of education, and participants with 12 years of education or more respectively. All the participants in the sample had a MMSE score above the cut-off points defined according to their educational level (Unschooled: $M = 20.5$, SD = 3.3; Unschooled-instructed: $M = 28.0$, SD = 1.3; Schooled: $M = 28.0$, SD = 2.0).

The final sample included 13 unschooled participants (Mean age = 45.4 years-old, SD = 18.9), 15 unschooled-instructed participants (Mean age = 41.5, SD = 16.9) and 15 schooled participants (Mean age = 47.4, SD = 14.8). The groups were matched for age, as confirmed by an ANOVA showing no significant difference in age between groups, $F(2, 43) < 1$. All participants were paid for their participation.

A *numerical screening pre-test* evaluating basic numerical skills (counting, transcoding, calculation, and use of numbers in their everyday life) was administered prior to the experimental tasks (see Supplementary Information). A univariate ANOVA with group as a between-subject factor was run for each basic numerical skill included in the screening pre-test. Bonferroni post-hoc contrasts indicated that the unschooled group performed worse than both the schooled and unschooled-instructed groups for all the measures ($p < .05$), except for the *Counting Principles* task for which there was no significant difference between groups (see Table 1). This suggests that participants who had not benefited from education in math understand counting principles and are able to count small sets of objects as efficiently as participants who received math instruction (see [53], for compatible data). For the other measures, the scores obtained by the unschooled participants were very heterogeneous, with some individuals performing extremely poorly and others reaching levels similar to those obtained by the schooled and unschooled-instructed participants. Except for the *Complex Calculation* task, the unschooled-instructed group did not significantly differ from the schooled group ($p \geq .05$). In sum, the results from the screening pre-test thus confirm that the numerical skills usually taught during math classes are much lower for most of the participants who had received no math education, and they provide further validation to the group assignment.

2.1.2. Materials and procedure

Participants were asked to compare two quantities and to choose the numerically largest as fast as possible. The largest quantity was equally distributed among the eight decades ranging from 20 to 90. The numerical ratio of the quantities to be compared was manipulated so that four ratios of decreasing difficulty were used (ratios were: 8:7, 8:6, 8:5 and 8:4). Two variants of the quantity comparison task were designed, with the same quantities but different presentation formats. In Exp. 1A, participants were asked to compare sets of dots. To avoid responses solely based on non-numerical continuous dimensions rather than on numerosity, two perceptual conditions were created. Half of the trials ($n = 32$) were congruent: the set with

[2] Since precise data about the time spent in adult education classes were missing for 5 of the 15 unschooled-instructed participants, standard deviation was here calculated on the basis of 10 participants only.

Table 1
Basic numerical skills: mean score, standard deviation, score range (in brackets) for each group and analysis of variance results.

	Schooled group (N=15)	Unschooled-instructed group (N=15)	Unschooled group (N=13)	F (2,40)
Counting sequence length (Max. 100)	$100^a\pm0.0$ [100–100]	$99.3^a\pm2.8$ [89–100]	$64.8^b\pm34.3$ [5–100]	15.52**
Counting principles (Max.9)	$8.7^a\pm.8$ [6–9]	$8.9^a\pm.5$ [7–9]	$7.5^a\pm2.5$ [0–9]	3.24
Arabic to verbal transcoding				
Number below 100 (Max. 9)	$9^a\pm.0$ [9–9]	$9^a\pm.0$ [9–9]	$5.4^b\pm3.3$ [0–9]	17.82**
Number above 100 (Max. 6)	$5.5^a\pm.7$ [4–6]	$4.6^a\pm.7$ [3–6]	$1.2^b\pm1.6$ [0–4]	63.14**
Verbal to Arabic transcoding				
Number below 100 (Max. 9)	$9^a\pm.0$ [9–9]	$9^a\pm.0$ [9–9]	$4.8^b\pm3.8$ [0–9]	18.63**
Number above 100 (Max. 6)	$5.1^a\pm.9$ [4–6]	$4.1^a\pm1.6$ [1–6]	$.8^b\pm1.6$ [0–4]	34.80**
Arithmetical facts score				
Addition (Max. 6)	$5.7^a\pm.6$ [4–6]	$5.4^a\pm.7$ [4–6]	$3.5^b\pm2.2$ [0–6]	10.75**
Subtraction (Max. 6)	$5.8^a\pm.6$ [4–6]	$4.7^{ab}\pm1.4$ [2–6]	$4.0^b\pm2.5$ [0–6]	4.38*
Multiplication (Max. 6)	$4.5^a\pm1.1$ [3–6]	$3.2^b\pm1.2$ [1–5]	$1.0^c\pm1.2$ [0–4]	30.23**
Division (Max. 6)	$4.9^a\pm.9$ [3–6]	$4.2^a\pm1.6$ [0–6]	$1.9^b\pm2.5$ [0–6]	11.96**
Total (Max. 24)	$20.9^a\pm2.4$ [16–23]	$17.5^a\pm3.1$ [11–21]	$10.4^b\pm6.8$ [0–21]	20.35**
Arithmetical facts time (s)				
Addition	$17.7^a\pm8.2$ [9–38]	$29.4^a\pm17.4$ [9–60]	$82.3^b\pm42.3$ [21–158]	23.77**
Subtraction	$16.7^a\pm8.3$ [7–31]	$42.2^a\pm29.6$ [7–120]	$87.6^b\pm50.1$ [17–208]	15.91**
Multiplication	$37.2^a\pm29.2$ [11–94]	$63.4^{ab}\pm36.9$ [12–136]	$88.8^b\pm29.4$ [38–128]	6.35**
Division	$30.4^a\pm16.3$ [11–61]	$65.7^{ab}\pm46.7$ [17–209]	$113.8^b\pm77$ [39–255]	8.22**
Total	$25.5^a\pm11.0$ [10–45]	$50.2^a\pm29.5$ [11–128]	$89.3^b\pm42.3$ [19–177]	15.51**
Complex calculation total				
Score (Max. 12)	$9.9^a\pm2.0$ [6–12]	$6.5^b\pm3.2$ [1–11]	$1.5^c\pm2.8$ [0–8]	33.61**
Numbers in the every-day life score	$13.9^a\pm.4$ [13–14]	$13.3^a\pm1.4$ [9–14]	$6.4^b\pm4.6$ [0–12]	33.40**

Means in the same row that do not share alphabetic superscripts differ at $p<.05$ regarding the Bonferroni post-hoc tests.

* $p<.05$.

** $p<.01$.

the largest number of dots had a total occupied area three times larger than the set with the smallest number of dots, so that the numerosity covaried positively with the total occupied area. The other half of the trials was incongruent: the set with the largest number of dots had a total occupied area three times smaller than the set with the smallest number of dots, so that the numerosity covaried negatively with the total occupied area. Dot size was heterogeneous within each set. In Exp. 1B, participants were asked to compare two-digit Arabic numbers. To prevent responses uniquely based on the rightmost digit (unit value), the unit–decade compatibility was manipulated [36]. Half of the trials involved compatible pairs of numbers: both the decade and unit values of the largest number were bigger than the decade and unit values of the smallest number (e.g. 78 vs. 36). The other half of the trials involved incompatible numbers: the largest number had a larger decade but a smaller unit than the smallest number (e.g. 76 vs. 38). Examples of stimuli used in Experiment 1 are depicted in Fig. 1.

A fixation point was displayed during 1000 ms in the center of the screen, followed by the presentation of two quantities: one on the left side of the screen, the other on the right. The two quantities remained visible until participants responded. The side of the correct response was counterbalanced so that the largest quantity appeared on the left side of the screen for half of the trials, and on the right side for the other half. Participants had to choose the largest quantity by pressing the corresponding key on the response box (left-key or right-key). Response times were recorded. Eight practice trials (4 with feed-back, 4 without feed-back) followed by 64 experimental trials were administered for Exp. 1A, and similarly for Exp. 1B.

2.2. Results

We first compared the mean percentage of errors to chance level (50%) for each group separately, using one sample t-tests. Then, the error rates and response times relative to the correct responses were entered in a mixed ANOVA, separately for Exp. 1A and Exp. 1B, with Condition and Ratio as within-subject factors, and Group as a between-subject factor. Mean error rates and response times for each Group as a function of Condition and Ratio are displayed in Fig. 2A and B for the comparison of dots (Exp. 1A) and of Arabic numbers (Exp. 1B) respectively.

2.2.1. Dot number comparison

In Exp. 1A, the mean percentage of errors was significantly below 50% for the schooled group, $t(14)=-14.90$, $p<.001$, for the unschooled-instructed group, $t(14)=-9.11$, $p<.001$ and for the unschooled group, $t(12)=-5.37$, $p<.001$. In fact, all the 43 participants had an error rate lower than 50% (range 3–45%), suggesting that none of them was responding randomly. Further, the ANOVA revealed that the error rate diminished with increasing ratio, demonstrating the signature of the approximate number system, $F(3, 120)=78.48$, $p<.001$, $\eta^2_p=.66$; Linear trend: $p<.001$. Furthermore, the congruency between the numerical and non-numerical cues influenced the capacity to compare sets of dots on the basis of number. Indeed, congruent trials led to lower error rates (8.7% errors) than incongruent trials (40.6%), $F(1, 40)=57.24$, $p<.001$, $\eta^2_p=.59$. This effect increased as the ratio approached one, i.e. it was larger for the most difficult comparisons, $F(3, 120)=14.66$, $p<.001$, $\eta^2_p=.27$.

Interestingly, the analysis revealed a main effect of Group, $F(2, 40)=4.63$, $p=.016$, $\eta^2_p=.19$. Bonferroni post-hoc comparisons indicated that participants from the unschooled group ($M=30.3\%$, SD=13.2, range=8–45) were overall more error-prone than participants from the schooled group (18.1%, SD=8.3, range=3–31; $p=.014$). The error rate for the unschooled-instructed group (25.5%, SD=10.4, range=11–41) did not significantly differ from either of the unschooled or schooled groups ($p=.74$ and $p=.20$, respectively). Here again, it is worth noting that the level of performance was very heterogeneous among participants, especially between participants from the unschooled group, as indexed by the range of individual scores.

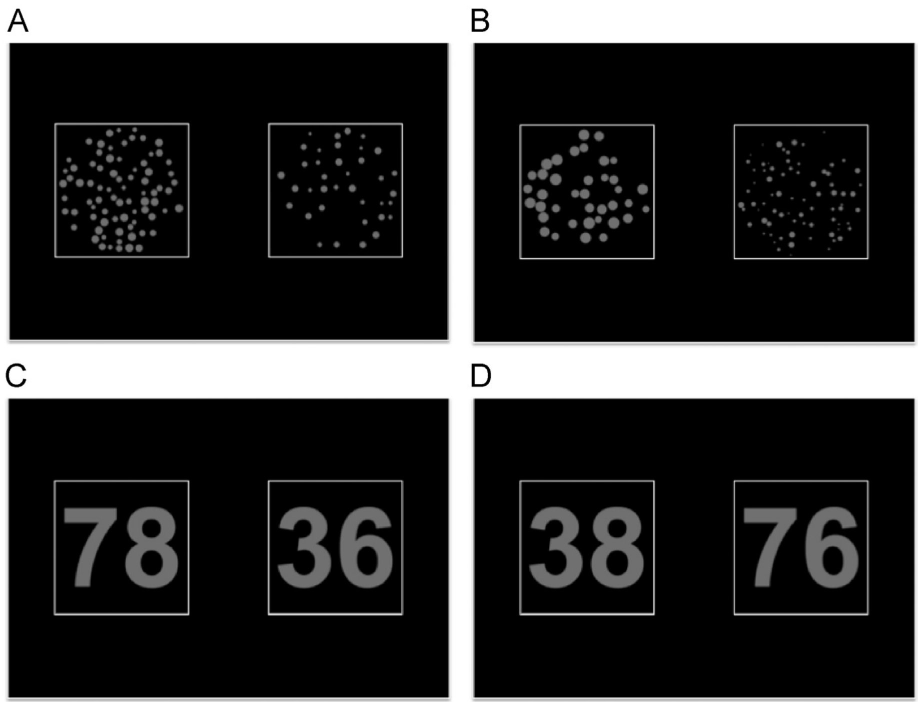

Fig. 1. Examples of stimuli presented in the Quantity Comparison Task (Experiment 1). The upper panels illustrate the dot number comparison task (Exp. 1A); the lower panels illustrate the Arabic number comparison task (Exp. 1B). Panels (A) and (B) correspond to congruent and incongruent trials, respectively. Panels (C) and (D) correspond to unit–decade compatible and incompatible trials, respectively.

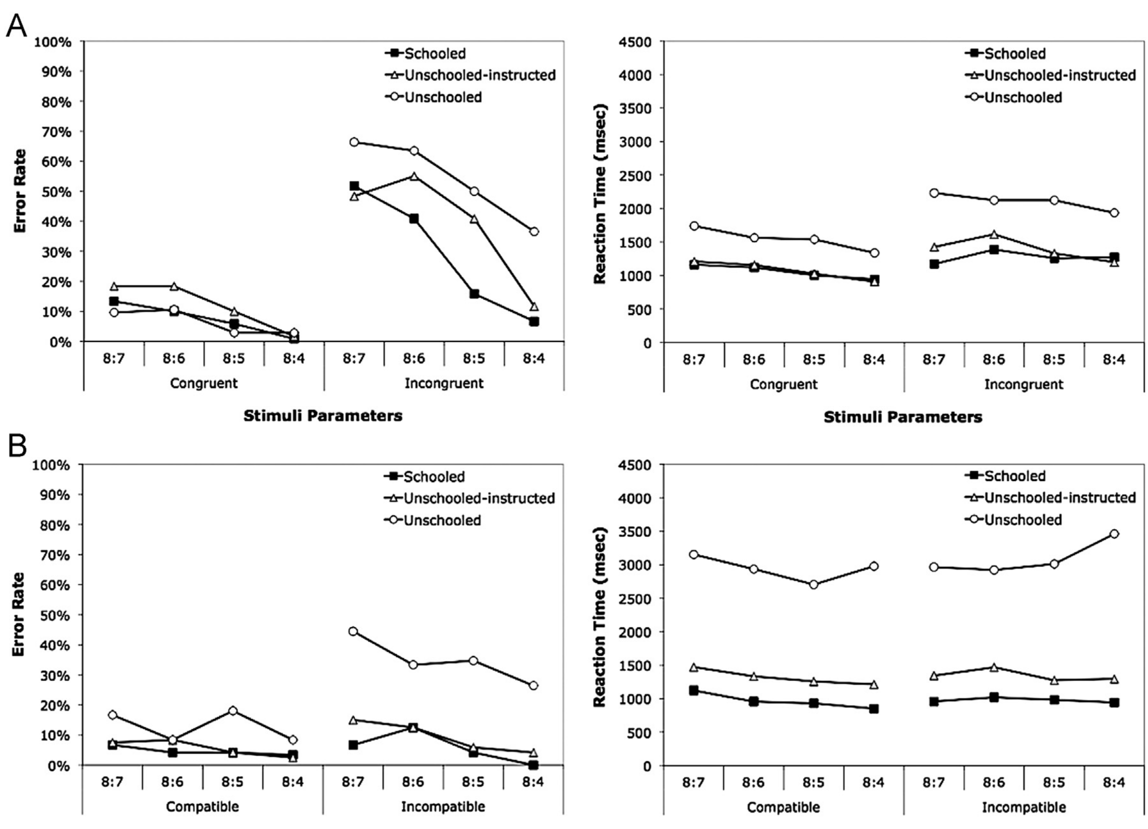

Fig. 2. Mean performance for each group and for each comparison task. Mean error rates (left panels) and mean response times (right panels) obtained by each group in the (A) dot number comparison task and in the (B) Arabic number comparison task, as a function of condition and ratio.

Importantly, the effect of ratio was less marked for the unschooled group than for the other two groups, as revealed by the significant Ratio × Group interaction, $F(6, 120)=3.38$, $p=.004$, $\eta_p^2=.15$. The error rate for the largest, easiest, ratio (8:4) was substantially lower for the schooled and unschooled-instructed groups (3.7% and 6.7% respectively) while it remained quite high for the unschooled group (19.7%), therefore leading to a smaller ratio effect for the latter. The Group difference was also modulated by the congruency between the numerical and non-numerical cues, $F(2, 40)=3.46$, $p=.041$, $\eta_p^2=.15$. A separate analysis for congruent and incongruent trials showed that the three groups did not differ for the congruent trials (6.5%, 12.1%, 7.5% errors, respectively for the unschooled, unschooled-instructed, and schooled groups, $p=.277$). By contrast, participants from the unschooled group had a mean error rate (54.1%) larger than that of the schooled group (28.8%, $p=.005$) and marginally larger than that of the unschooled-instructed group (39.0%, $p=.08$) when the total area occupied by the dots was incongruent with the number of dots (Main effect of group, $p=.02$). However, participants from the unschooled group did not uniquely base their responses on non-numerical parameters such as area, since incongruent trials led to an overall error rate much smaller than 100%, especially for the largest numerical ratios. The triple interaction was not significant, $p>.10$.

Regarding RTs, as expected, the analysis revealed a significant effect of ratio, $F(3, 96)=13.93$, $p<.001$, $\eta_p^2=.30$; Linear trend: $p<.001$. The effect of Condition was also significant, $F(1, 32)=13.03$, $p=.001$, $\eta_p^2=.29$, with faster RTs for congruent trials (1261 ms) than incongruent trials (1487 ms). Finally, the unschooled group ($M=1665$ ms, SD=547, range=731–2579) was slower at comparing sets of dots than both the unschooled-instructed (1116 ms, SD=334, range=767–1778) and schooled groups (1183 ms, SD=255, range=560–1531; $ps<.05$), who did not differ from each other ($p>.05$), $F(2, 32)=9.10$, $p=.001$, $\eta_p^2=.36$. No other significant effect was found, all $ps>.10$.

2.2.2. Arabic number comparison

In Exp. 1B, all analyses were based on data from 39 participants because four participants from the unschooled group refused to complete the Arabic number comparison task. In fact, these four participants had huge difficulties to process Arabic numerals from across the range used in this task, as revealed by the *Arabic to Verbal Transcoding* subtest in which they reached very poor performance, even for the numerals below 100 (see Table 1).

The mean percentage of errors was significantly lower than 50% for the schooled group, $t(14)=-21.16$, $p<.001$, for the unschooled-instructed group, $t(14)=-26.67$, $p<.001$ and for the unschooled group, $t(8)=-5.54$, $p=.001$. More precisely, all the 39 participants had an error rate below 50% (range 0–41%), showing that they did not respond randomly. The ANOVA revealed that the error rate diminished with increasing ratio, $F(3, 108)=10.58$, $p<.001$, $\eta_p^2=.23$; Linear trend: $p<.001$, and was lower for the unit–decade compatible trials (7.7%) than for incompatible trials (16.6%), $F(1, 36)=31.85$, $p<.001$, $\eta_p^2=.47$. The error rate varied with Group, $F(2, 36)=12.49$, $p<.001$, $\eta_p^2=.41$. Bonferroni post-hoc comparisons indicated that the unschooled group (23.8%, SD=14.2, range=2–41) had a higher error rate than both the unschooled-instructed (7.5%, SD=6.2, range=0–22) and schooled groups (5.2%, SD=8.2, range=0–33) when asked to compare two-digit Arabic numbers ($ps\leq.001$)[3]. The schooled and unschooled-instructed groups did not differ from each other ($p>.05$). Again, performance was very heterogeneous among participants. Further, the discrepancy between the unschooled group and the two other groups seemed to be slightly more pronounced for the smallest ratios, as revealed by a significant Ratio × Group interaction, $F(6, 108)=2.21$, $p=.048$, $\eta_p^2=.11$. The group difference was also much larger for the incompatible trials (34.7%, 9.4%, 5.8% errors, respectively for the unschooled, unschooled-instructed, and schooled groups) than for the compatible trials (12.8%, 5.6%, 4.6% errors respectively), $F(2, 36)=14.26$, $p<.001$, $\eta_p^2=.44$.

Regarding RTs, the analysis showed a significant effect of Group, $F(2, 36)=24.66$, $p<.001$, $\eta_p^2=.58$. Participants from the unschooled group (3066 ms, SD=1158, range=1583–4606) were extremely slow to compare two-digit Arabic numbers. Bonferroni post-hoc comparisons indicated that they were slower than both the unschooled-instructed (1321 ms, SD=664, range=711–2996; $p<.001$) and schooled groups (966 ms, SD=219, range=644–1377; $p<.001$), who did not differ from each other ($p>.05$). The effect of Condition was marginally significant, $F(1, 36)=2.68$, $p=.10$, $\eta_p^2=.07$, with shorter reaction times for unit–decade compatible trials (1738 ms) than for incompatible trials (1899 ms). No other significant effect was found.

2.3. Discussion

Regarding the Arabic number comparison task (Exp. 1B), the results showed that although adults who never received math education are not completely unable to access numerical information from Arabic numerals, their mastery of the place-value structure of the Arabic number system is generally limited. Indeed, four of them refused to complete the task and those who participated committed a lot of errors in addition to being extremely slow. Moreover, the fact that the unschooled group was less prone than the others to disregard the irrelevant unit-value in the incompatible trials is an indication that the integration of the magnitude of decades and units into the place-value structure of the Arabic number system constitutes a very demanding process for the majority of the participants from this group. Further, the observation that the unschooled participants had higher error rates and longer processing times for the compatible trials as well suggests either their access to number magnitude from Arabic number symbols is less efficient or that their capacities to process number magnitude itself are weaker than those of participants who received math education.

Results from Exp. 1A, which did not involve any number symbols, seem coherent with the latter view. Indeed, the unschooled group performed more poorly and exhibited an effect of numerical ratio different from that of both the other groups in the nonsymbolic number comparison task, suggesting that the core number processing skills of adults who did not receive education in math are less precise than those of adults who benefited from it. This finding might be taken to provide further support to the hypothesis that mathematical learning constitutes one factor influencing the refinement of the approximate number processing skills during the life course. However, the observation that the unschooled group produced a larger number of errors only when information on numerosity was incompatible with information on the non-numerical area dimension led us to consider an alternative (though not mutually exclusive) interpretation. It might be the case that uninstructed participants are less able than instructed adults to focus on the numerical properties of the figures and to disengage their attention from the continuous non-numerical variables. This specific difficulty could arise from a more general trend for uninstructed participants to favor holistic rather analytic processing, which prevents focusing on specific dimensions only [5,46]. Experiment 2 was run to investigate further the hypothesis of a specific difference in numerical magnitude handling, while at the same time eliminating the effect of a general cognitive trend towards holistic processing.

[3] It is worth noting that since about one fourth of the participants from the unschooled group refused to complete the Arabic number comparison task, the group difference observed between the unschooled group and the other two groups in this task might be even larger than depicted here.

3. Experiment 2

The Forced-Choice Mapping Task was designed to assess whether the poorer performance observed for the participants from the unschooled group in Exp. 1 was solely due to an inability to focus their attention on the numerical properties of the stimuli or whether it was also related to a more specific difference in the acuity of the approximate number system. To address this aim, the task was designed so that the continuous non-numerical variables could not provide any clue about the correct response.

3.1. Method

3.1.1. Participants

The sample of participants was the same as in Experiment 1.

3.1.2. Materials and procedure

In Exp. 2 (*Forced-Choice Mapping* task) participants had to match quantities numerically. A fixation point was displayed during 2000 ms in the center of the screen, followed by the presentation of a target-quantity during 1000 ms. After a 400 ms blank-interval, three choice-quantities (a quantity numerically matching the target and two distractors) were horizontally displayed side by side on the screen, numerically increasing from left to right. Among the three choice-quantities that remained visible until response, participants had to identify the panel that numerically matched the target-quantity. Participants indicated their response by pointing on the screen to the quantity they chose. The experimenter then pressed the corresponding key on the response box.

The target-quantity ranged from 4 to 49; the distractors from 2 to 98. The correct response was equally distributed among the three positions: one third corresponded to the smallest value (located on the extreme-left of the screen), one third to the mid-range value (on the center), and one-third to the largest value (on the extreme-right). The two distractors were quantities corresponding to 8:4, 8:5, 8:6 or 8:7 (or inversely 4:8, 5:8, 6:8 and 7:8) of the target-quantity. The trial difficulty was manipulated so that the target-quantity and the distractors were either numerically close or distant. When the target-quantity was a mid-range value, the easy trials included numerically far distractors (ratio of 8:4 or of 8:5), whereas the difficult trials involved numerically close distractors (ratio of 8:7 or of 8:6). When the target-quantity was either the smallest or the largest value, the easy trials implied systematically one very distant distractor (ratio of 8:4), and the difficult trials implied one very close distractor (ratio of 8:7), whereas the other distractor had an intermediate ratio (see Table 2, for some examples). Fifteen practice trials were first administered (with feed-back) followed by 96 experimental trials.

Several variants of the Forced-Choice Mapping task were used, with either nonsymbolic stimuli only (sets of dots) or a combination of nonsymbolic (sets of dots) and symbolic stimuli (numbers visually presented in an Arabic format and simultaneously read aloud by the experimenter). Each variant of the Forced-Choice Mapping task involved the same numerosities. In the *NS-to-NS* format, the target-quantity and the choice-quantities were all nonsymbolic (NS mapping condition). To prevent responses based on non-numerical continuous variables rather than on numerosity, the set of dots presented as target-quantity had a total occupied area three times smaller than the choice-quantities and the total occupied area was the same for the three choice-quantities. Since the total area of the choice-quantities did not vary with the number of dots, area was consequently not providing any clue about the correct response. By contrast, the individual dot size, which was held constant within each set, varied with number. However, it was not informative of the correct response for two reasons. First, the individual dot size of the correct choice was three times larger than that of the target-quantity. Second, the correct response could not be derived on the basis of the individual dot size of the choice-quantities because the correct response was not systematically associated to a specific individual dot size but was rather equally distributed among the three positions, therefore corresponding to the numerosity with either the smallest, or intermediate, or largest dots, each in one-third of the trials respectively. In the *NS-to-S* format, the target-quantity was nonsymbolic and the choice-quantities were symbolic. In the *S-to-NS* format, the target-quantity was symbolic and the choice-quantities were nonsymbolic. Among the three choice-quantities, the total occupied area was the same for each set of dots. Dot size was held constant within a set. The two variants of the Forced-Choice Mapping task that involved a mapping between nonsymbolic and symbolic stimuli were put together for the analyses (NS/S mapping condition). Examples of stimuli used in Experiment 2 are depicted in Fig. 3.

Table 2
Examples of quantities displayed in the forced-choice mapping task for distant and close distractors trials.

	Target	Choices-Quantities		
Distant distractors trial				
Small value	*48*	*48*	77	96
Mid-range value	*49*	25	*49*	98
Large value	*46*	23	29	*46*
Close distractors trial				
Small value	*47*	*47*	54	63
Mid-range value	*48*	42	*48*	55
Large value	*49*	37	43	*49*

3.2. Results and discussion

Two participants from the unschooled group were unable to perform the Forced-Choice Mapping Task and were excluded from the analyses. Two additional participants from this group obtained a mean percentage of correct responses (32%) that was not above chance (33%). However, these two participants were kept in the analysis because they performed above chance in at least one of the conditions of the task, suggesting that they had understood the instructions correctly. All analyses were thus based on data from 41 participants. Regarding the NS/S condition, the results showed that the mean percentage of correct responses was above chance whatever the group and whatever the distance between the target and the distractors (see Table 3). For the NS condition, the mean percentage of correct responses was above chance for each group of participants, except for the most difficult trials (close distractors) for which the unschooled group reached very poor performance.

A $2 \times 2 \times 3$ mixed ANOVA was run on the mean percentage of correct responses with Condition (NS Mapping vs. NS/S Mapping) and Distance (close vs. distant distractors) as within-subject factors, and Group as a between-subject factor. Results showed significant differences between groups, $F(2, 38)=13.84$, $p<.001$, $\eta_p^2=.42$. Bonferroni comparisons indicated that the unschooled group obtained a lower score (39.1% correct responses) than both the unschooled-instructed and schooled groups (47.3% and 52.6% respectively; $ps<.05$), who did not differ from each other ($p>.05$). The NS mapping led to lower performance (42.9%) than the NS/S mapping (49.8%), $F(1, 38)=54.56$, $p<.001$, $\eta_p^2=.59$. The Group by Format interaction was not significant, indicating that the unschooled group had poorer performance than the two other groups both in the NS/S condition as well as in the NS condition, $F(1, 38)=2.07$, $p=.141$, $\eta_p^2=.09$. The fact that the participants from the unschooled group displayed poorer

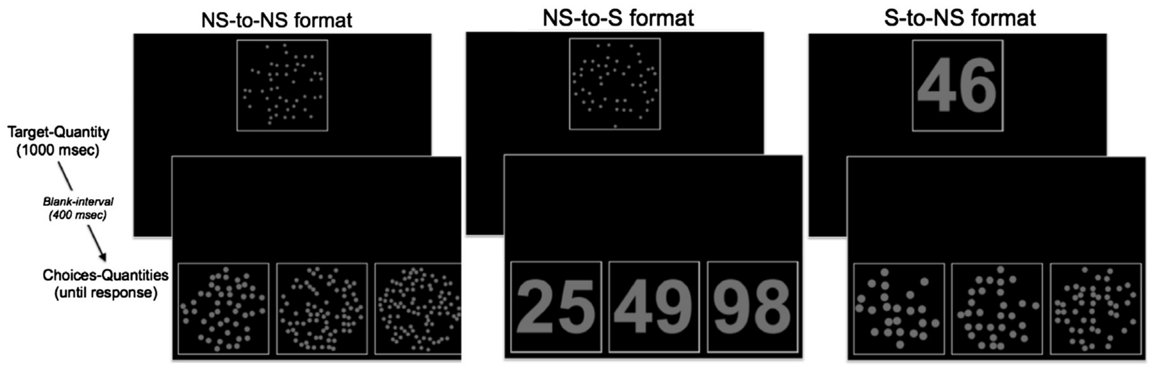

Fig. 3. Illustration of the Forced-Choice Mapping task procedure and stimuli. From left to right: NS-to-NS format; NS-to-S format and S-to-NS format. In the examples provided here, the correct response is located on the left, the middle and the right position respectively. Notice that the total occupied areas of the choice-quantities in the NS–NS format are equated and three times larger than that of the target-quantity.

Table 3
Mean percentage of correct responses, and analysis of the differences between chance level performance and percentage of correct responses, as function of group, condition and distance.

	Task	Mean (SD)	*df*	*t* (Test value=33)
Schooled group	NS mapping			
	Distant distractor trials	54.2 (12.2)	14	6.71**
	Close distractor trials	41.4 (10.7)	14	3.04**
	NS/S mapping			
	Distant distractor trials	64.8 (7.9)	14	15.6**
	Close distractor trials	49.9 (5.1)	14	12.9**
Unschooled-instructed group	NS mapping			
	Distant distractor trials	47.1 (10.6)	14	5.1**
	Close distractor trials	41.9 (4.8)	14	7.2**
	NS/S mapping			
	Distant distractor trials	56.5 (9.3)	14	9.8**
	Close distractor trials	43.8 (6.3)	14	6.7**
Unschooled group	NS mapping			
	Distant distractor trials	38.5 (8.3)	10	2.2*
	Close distractor trials	34.1 (7.8)	10	.5
	NS/S mapping			
	Distant distractor trials	44.6 (8.5)	10	4.5**
	Close distractor trials	39.2 (6.7)	10	3.1**

* $p<.05$.
** $p<.01$.

performance than the two other groups in the purely nonsymbolic variant of the task suggests that they have less developed approximate number processing skills. Finally, we observed a significant effect of Distance, $F(1, 38)=78.95$, $p<.001$, $\eta_p^2=.68$ and a significant Group by Distance interaction, $F(2, 38)=6.03$, $p=.005$, $\eta_p^2=.24$ indicating that the gain provided by the easier trials that involve numerically far distractors was smaller for the unschooled group than for the unschooled-instructed group, and smaller for the unschooled-instructed group than for the schooled group. This finding suggests that the subjective overlap between numerically adjacent quantities is greater for the participants from the unschooled group, providing further support to the conclusion that their approximate number processing skills are less precise than those of participants who received education in mathematics. No other significant effect was found, all $ps \geq .10$.

4. General discussion

A recent study in the domain of language demonstrated that human brain circuits show considerable plasticity in response to reading acquisition, and in particular that literacy induces functional changes in the cortical networks involved in phylogenetically ancient cognitive skills, such as speech and visual object recognition [9]. Somewhat similarly, the current findings show that the acquisition of culturally determined skills is also capable of modifying core cognitive competences in the domain of numeracy. In the current study we compared several groups of adults who live in the same Western cultural environment but who differ dramatically in the type and level of math education they had received. The present data provide the first clear evidence that large number magnitude processing skills are affected by the experience afforded by the education in mathematics. Western adults who had received no formal instruction in mathematics displayed longer response times, higher error rates, and a smaller numerical ratio effect on large nonsymbolic number comparison than Western adults who had acquired exact number skills through math education, particularly when non-numerical cues were incongruent with numerosity. Moreover, the forced-choice mapping task confirmed the existence of group differences in the ability to approximately process large number magnitude, by showing that adults in the unschooled group were poorer at discriminating a target value from numerically distant quantities, even when nonsymbolic stimuli only were presented. The findings suggest that the acquisition of exact numerical knowledge through mathematical education contributes to enhance the precision of the approximate number system, leading adults who have benefitted from instruction to develop more accurate approximate number processing skills. The observation that the schooled and unschooled-instructed groups reached similar performance across the two tasks used in the current study further suggests that such a refinement in numerical perception may occur late in life, and also highlights the importance of mathematical education rather than schooling per se. In other words, a factor that seems determinant for the enhancement of the approximate number system is receiving instruction in math, whatever the system of education, its organization, curriculum or methodology.

Several factors can be invoked to explain this refinement. A first possibility is that math education modifies the importance that individuals attribute to numerical information and a second one is that certain numerical activities on which math education focuses might directly affect the efficiency of the approximate number system. Regarding the first hypothesis, math education might influence number processing by enhancing the salience of numerical properties over other aspects of objects or events. Past studies have demonstrated that, with age, it becomes increasingly difficult to ignore number, even when the numerical features of the stimuli are irrelevant to the task [37,44]. One little noticed consequence of mathematical instruction may be to induce individuals to gradually attribute more and more weight to numerical information over other features and dimensions of their environment. The observation that numerosity did not preempt non-numerical dimensions for the participants from the unschooled group in the incongruent comparison trials and the fact that their level of performance matches that of 5 and 6-year-old preschoolers when comparable ratios are considered in similar experimental situations [2,44], are coherent with the view that education in mathematics might induce the predominance of number over other perceptual features.

Regarding the hypothesis of a direct influence of math education on the approximate number system, the formal utilization of Arabic numerals might fundamentally transform number processing. Like the verbal symbols, the Arabic numerals allow one to use numbers in reference to their discrete, exact value, and to extend their range infinitely. Beyond that, because the Arabic numeral system is based on few symbols and produces compact combinatorial expressions even for large numbers, the apprehension and manipulation of numbers is rendered easier. Furthermore, the place-value coding of the Arabic numeral system considerably simplifies the learning of exact arithmetic. Overall, mainly because of its notational economy and compactness, it is really with the introduction of the Arabic numeral system that an intensive use of large and not only small numbers can take place. Such a strengthened utilization of numbers could further precise the underlying representations that children form about numbers. Interestingly, the notion that the use of numerals might refine the precision with which mental representations of numbers are accessed has received some support in recent neuroimagery and neural simulation studies [42,47]. Another way in which math education might impact on number processing is through the introduction of exact arithmetic. Arithmetic is a powerful drive to create relations across numbers and to manipulate them extensively. Through arithmetic learning, people can appreciate the quantitative effects of number operations and how numbers interact. Also through repeated practice, the constitutive components of a number can be better apprehended. In that way, operating on numbers through arithmetic constitutes an additional opportunity to better understand what numbers stand for and to better apprehend the relations between numerals and numerosities, thereby increasing the distinctiveness of the underlying number magnitude representations.

More generally, one critical element provided by math education is experience with numbers. During math lessons, students are engaged in the exact manipulation of numbers, so that they become more familiar with the range of numbers to which they are exposed. During kindergarten and the first grades of elementary school, teachers traditionally train children to learn basic arithmetical concepts such as exact addition and exact subtraction by using single-digit numbers. It is only in older children, once these fundamental concepts are acquired, that teachers begin to introduce larger numbers in exact calculation, with the use of multi-digits numerals. Therefore, one inevitable correlate of the level of math education is the degree of familiarity with numbers, so that beginners are familiar with small numbers only, while those who are more advanced are acquainted with small as well as larger numbers. As a consequence, the experience and familiarity with number might also be a key factor responsible for the refinement of the number magnitude skills. This hypothesis could constitute an additional explanation of the fact that the unschooled-instructed group did usually not differ from the schooled group. Indeed, due to their professional occupation, most of the participants from the unschooled-instructed group were used to perform arithmetic operations on large numbers in their everyday life, for instance through practicing money exchange. Variations in familiarity and daily use of large numbers could also account for the large heterogeneity observed in the magnitude tasks for the unschooled group, with a few participants from this group reaching performance similar to that of schooled participants. Some support for this view can be seen in the relatively high scores obtained by those unschooled participants in the numerical screening test, in particular with regards to the use of numbers in the everyday life. Interestingly, although the number of unschooled participants is very limited, there was a significant correlation between the use of numbers in the everyday life and the error rate in the nonsymbolic comparison task ($r\,(13)=-.57$, $p=.04$). These observations are thus compatible with the idea that the experience with numbers, in addition to years of education, may be one important factor determining performance in the magnitude-processing tasks used in the present study.

Importantly, this proposal helps reconcile the current data with those reported very recently by Zebian and Ansari [53], who showed, contrary to us, that minimally instructed adults did not differ significantly from highly instructed adults in comparing nonsymbolic quantities. However, in their study, the authors presented small quantities ranging from one to nine only, i.e. very basic numerosities that are encountered daily (e.g., the 10 fingers, the 12 hours, the limited number of family members) and with which even adults who did not benefit from math education are most likely very familiar. The observation that the nonsymbolic approximate number skills of minimally instructed adults are not statistically different from those of highly instructed adults when very small numbers are involved [53] whereas they are clearly less precise for large numbers gives further credence to the hypothesis that experience with numbers plays an important role in the development and refinement of number magnitude processing mechanisms.

In sum, the current results challenge the dominant interpretation of the developmental studies showing a specific association between approximate and exact number skills [14,20–22,25,28,31,32,41]. The first and dominant explanation is that the approximate number system serves as a foundation for the acquisition of exact number skills, such as counting and arithmetical skills, and that inter-individual variations in the efficiency of the approximate number system causally determines exact number abilities [6,7,45,28]. A second interpretation of the association is that the reverse might occur, i.e., that the acquisition of exact number competences through math education and prolonged exposure to numerical notations modifies or refines the approximate number system. For instance, Halberda and colleagues [20] found a correlation between approximate number skills assessed at the age of 14 and past mathematical achievement scores, a result which is compatible with both interpretations. The present data provide the first clear evidence that the second, less dominant, view constitutes a viable explanation (see also [33], in revision, for converging data in kindergarten children). Of course, the current results also leave the way open to a third interpretation according to which both causal directions would be at play, with the existence of reciprocal influences during development between the exact and approximate number skills. In accordance with such an account, the observation of dyscalculic children who experience difficulty in exact calculation as well as in approximate number tasks (e.g., [32,41]) might reflect a deficit of the core numerical magnitude competence, a specific difficulty in grasping numerical symbol systems, or possibly reciprocal influences between both components (see also [34]). In conclusion, the current findings underline the powerful influence of enculturation on biologically determined cognitive skills in the domain of numeracy. They clearly indicate that the possibility of reciprocal influences between exact and approximate number systems should be considered more systematically in future studies of numerical development and acquisition disorders.

Acknowledgments

The present work was partly supported by a Concerted Research Action grant (ARC-06/11-342) funded by the Direction Générale de l'Enseignement non obligatoire et de la Recherche scientifique—Communauté Française de Belgique.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.tine.2013.01.001.

References

[1] Anthony JC, LeResche L, Niaz U, von Korff MR, Folstein MF. Limits of the Mini-Mental State as a screening test for dementia and delirium among hospital patients. Psychological Medicine 1982;12(2):397–408.
[2] Barth H, La Mont K, Lipton J, Spelke ES. Abstract number and arithmetic in preschool children. Proceedings of the National Academy of Sciences 2005;102(39):14116–21.
[3] Bertolucci PH, Brucki SM, Campacci SR, Juliano Y. The Mini-Mental State Examination in a general population: impact of educational status. Arquivos de Neuro-Psiquiatria 1994;52(1):1–7.
[4] Brannon EM, Abbott S, Lutz DJ. Number bias for the discrimination of large visual sets in infancy. Cognition 2004;93(2):B59–68.
[5] Brito-Mendes C, Morais J, Kolinsky R. Analytical and holistic processing in post-perceptual visual cognition. In: Morais J, Ventura P, editors. Studies on the mind: A tribute to Carlos Brito-Mendes. Lisbon, Portugal: Educa; 2005. p. 177–96.
[6] Butterworth B. The mathematical brain. London, England: Macmillan; 1999.
[7] Dehaene S. Precis of the number sense. Mind & Language 2001;16:16–36.
[8] Dehaene S, Dehaene-Lambertz G, Cohen L. Abstract representations of numbers in the animal and human brain. Trends in Neurosciences 1998;21(8):355–61.
[9] Dehaene S, Pegado F, Braga LW, Ventura P, Filho GN, Jobert A, Dehaene-Lambertz G, et al. How learning to read changes the cortical networks for vision and language. Science 2010;330(6009):1359–64.
[10] Deloche G, Souza L, Braga L, Dellatolas G. A calculation and number processing battery for clinical application in illiterates and semi-literates. Cortex 1999;35(4):503–21.
[11] Feigenson L, Dehaene S, Spelke ES. Core systems of number. Trends in Cognitive Sciences 2004;8(7):307–14.
[12] Folstein MF, Folstein SE, McHugh PR. Mini-mental state: a practical method for grading the cognitive state of patients for the clinician. Journal of Psychiatric Research 1975;12(3):189–98.
[13] Frank MC, Everett DL, Fedorenko E, Gibson E. Number as a cognitive technology: evidence from Pirahã language and cognition. Cognition 2008;108(3):819–24.
[14] Gilmore CK, McCarthy SE, Spelke ES. Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. Cognition 2010;115(3):394–406.
[15] Göbel SM, Rushworth MFS, Walsh V. rTMS disrupts the representation of small numbers in supramarginal gyrus. NeuroImage 2001;13(6, Supplement):409.
[16] Göbel SM, Walsh V, Rushworth MFS. The mental number line and the human angular gyrus. NeuroImage 2001;14(6):1278–89.
[17] Gordon P. Numerical cognition without words: evidence from Amazonia. Science 2004;306(5695):496–9.
[18] Guerreiro M, Silva AP, Botelho MA, Leitão O, Castro-Caldas A, Garcia C. Adaptação à população portuguesa da tradução do Mini Mental State Examination (MMSE). Revista Portuguesa de Neurologia 1994;1:9–10.
[19] Halberda J, Feigenson L. Developmental change in the acuity of the number sense: the approximate number system in 3-, 4-, 5-, and 6-year-olds and adults. Developmental Psychology 2008;44(5):1457–65.
[20] Halberda J, Mazzocco MMM, Feigenson L. Individual differences in non-verbal number acuity correlate with maths achievement. Nature 2008;455:665–8.
[21] Holloway ID, Ansari D. Mapping numerical magnitudes onto symbols: the numerical distance effect and individual differences in children's mathematics achievement. Journal of Experimental Child Psychology 2009;103(1):17–29.
[22] Inglis M, Attridge N, Batchelor S, Gilmore C. Non-verbal number acuity correlates with symbolic mathematics achievement: but only in children. Psychonomic Bulletin & Review 2011;18(6):1222–9.
[23] Izard V, Sann C, Spelke ES, Streri A. Newborn infants perceive abstract numbers. Proceedings of the National Academy of Sciences 2009;106(25):10382–5.
[24] Li G, Cheung R, Gao J, Lee T, Tan L, Fox P, Jack C, et al. Cognitive processing in Chinese literate and illiterate subjects: an fMRI study. Human Brain Mapping 2006;27(2):144–52.
[25] Libertus ME, Feigenson L, Halberda J. Preschool acuity of the approximate number system correlates with school math ability. Developmental Science 2011;14(6):1292–300.
[26] Lipton JS, Spelke ES. Origins of number sense. Large-number discrimination in human infants. Psychological Science 2003;14(5):396–401.
[27] Lobrot M. Batterie d'e´preuves pour mesurer la lecture et l'orthographe: Manuel. Paris, France: Editions et Application Psychologiques; 1980.
[28] Mazzocco MMM, Feigenson L, Halberda J. Preschoolers' precision of the approximate number system predicts later school mathematics performance. PLoS ONE 2011;6(9):e23749.
[29] Morais J, Bertelson P, Cary L, Alegria J. Literacy training and speech segmentation. Cognition 1986;24(1–2):45–64.
[30] Morais J, Cary L, Alegria J, Bertelson P. Does awareness of speech as a sequence of phones arise spontaneously? Cognition 1979;7(4):323–31.
[31] Mundy E, Gilmore CK. Children's mapping between symbolic and nonsymbolic representations of number. Journal of Experimental Child Psychology 2009;103(4):490–502.
[32] Mussolin C, Mejias S, Noël M-P. Symbolic and nonsymbolic number comparison in children with and without dyscalculia. Cognition 2010;115(1):10–25.
[33] Mussolin C, Nys J, Content A, Leybaert J. Symbolic number abilities predict later approximate number system acuity in young children, in preparation.
[34] Noël M-P, Rousselle L. Developmental changes in the profiles of dyscalculia: an explanation based on a double exact-and-approximate number representation model. Frontiers in Human Neuroscience 2011;5:165.
[35] Notebaert K, Reynvoet B. Different magnitude representations in left and right hemisphere: evidence from the visual half field technique. Laterality 2009;14(3):228–45.
[36] Nuerk H, Weger U, Willmes K. Decade breaks in the mental number line? Putting the tens and units back in different bins Cognition 2001;82(1):B25–33.
[37] Nys J, Content A. Judgement of discrete and continuous quantity in adults: number counts!. Quarterly Journal of Experimental Psychology 2012;65(4):675–90.
[38] O'Connor DW, Pollitt PA, Treasure FP, Brook CP, Reiss BB. The influence of education, social class and sex on Mini-Mental State scores. Psychological Medicine 1989;19(3):771–6.
[39] Petersson KM, Reis A, Ingvar M. Cognitive processing in literate and illiterate subjects: a review of some recent behavioral and functional neuroimaging data. Scandinavian Journal of Psychology 2001;42(3):251–67.
[40] Piazza M. Neurocognitive start-up tools for symbolic number representations. Trends in Cognitive Sciences 2010;14:542–51.
[41] Piazza M, Facoetti A, Trussardi AN, Berteletti I, Conte S, Lucangeli D, Dehaene S, et al. Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. Cognition 2010;116(1):33–41.
[42] Piazza M, Pinel P, Le Bihan D, Dehaene S. A magnitude code common to numerosities and number symbols in human intraparietal cortex. Neuron 2007;53(2):293–305.
[43] Pica P, Lemer C, Izard V, Dehaene S. Exact and approximate arithmetic in an Amazonian indigene group. Science 2004;306(5695):499–503.
[44] Rousselle L, Noël M-P. The development of automatic numerosity processing in preschoolers: evidence for numerosity-perceptual interference. Developmental Psychology 2008;44(2):544–60.
[45] Spelke ES. Core knowledge. American Psychologist 2000;55(11):1233–43.
[46] Ventura P, Pattamadilok C, Fernandes T, Klein O, Morais J, Kolinsky R. Schooling in western culture promotes context-free processing. Journal of Experimental Child Psychology 2008;100(2):79–88.
[47] Verguts T, Fias W. Representation of number in animals and humans: a neural model. Journal of Cognitive Neuroscience 2004;16(9):1493–504.
[48] Wood JN, Spelke ES. Infants' enumeration of actions: numerical discrimination and its signature limits. Developmental Science 2005;8(2):173–81.
[49] Xu F. Numerosity discrimination in infants: evidence for two systems of representations. Cognition 2003;89(1):B15–25.
[50] Xu F, Arriaga R. Number discrimination in 10-month-old infants. British Journal of Developmental Psychology 2007;25(1):103–8.
[51] Xu F, Spelke ES. Large number discrimination in 6-month-old infants. Cognition 2000;74(1):B1–11.
[52] Xu F, Spelke ES, Goddard S. Number sense in human infants. Developmental Science 2005;8(1):88–101.
[53] Zebian S, Ansari D. Differences between literates and illiterates on symbolic but not nonsymbolic numerical magnitude processing. Psychonomic Bulletin & Review 2012;19(1):93–100.