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EDUCATION ENHANCES THE ACUITY OF THE NON-VERBAL APPROXIMATE NUMBER SYSTEM

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Abstract

All humans share a universal, evolutionarily ancient approximate number system (ANS) that estimates and combines the number of objects in sets with ratio-limited precision. Inter-individual variability in the acuity of the ANS correlates with mathematical achievement, but the causes of this correlation have never been established. We acquired psychophysical measures of ANS acuity in child and adult members of an indigene group in the Amazon, the Mundurucu, who have a very restricted numerical lexicon and highly variable access to mathematical education. By comparing Mundurucu subjects with or without access to schooling, we demonstrate that education significantly enhances the acuity with which sets of concrete objects are estimated. These results speak in favor of an important effect of culture and education on basic number perception. We hypothesize that symbolic and non-symbolic numerical thinking mutually enhance one another over the course of mathematics instruction.

Keywords

Perception; Sociocultural Factors; Cross Cultural Differences; Mathematical Ability

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INTRODUCTION

In societies for which education is universal, child development, learning and instruction tend to be inextricably confounded. Their correlation makes it hard to investigate the causes of cognitive change during development. In many domains competence is present in infancy and continuously improves during childhood, but also correlates with academic scores in school-based tests. Thus, we cannot easily determine how much of this developmental progression relates to brain maturation, to cultural learning, and to schooling.

Here we approach this question in the number domain. Basic numerical competences, including the ability to estimate and mentally combine approximate numbers of objects in sets, are present very early in life (Izard, Dehaene-Lambertz, & Dehaene, 2008). Such skills (associated with a system in parietal cortex, or Approximate Number System, ANS) follow Weber's law: the extent to which two numerosities can be discriminated is determined by their ratio. The acuity of the ANS can therefore be indexed by the minimum ratio between two quantities that can be accurately discriminated (Weber fraction). This acuity undergoes a process of refinement (see for review Halberda & Feigenson, 2008; Piazza, 2010) during infancy and through adulthood (Figure 1A).

The ANS is thought to be a basic building block for the later cultural construction of abstract, symbolic number concepts (Dehaene, 1997; Gelman & Butterworth, 2005; Gilmore, McCarthy, & Spelke, 2007; Piazza, 2010; Piazza & Dehaene, 2004) (but see (Butterworth, 2010; Le Corre & Carey, 2007). Indeed, recent studies have revealed significant correlations between ANS acuity and mathematical achievement, in normally achieving (Gilmore, McCarthy, & Spelke, 2010; Halberda, Mazzocco, & Feigenson, 2008; Mazzocco, Feigenson, & Halberda, 2011b) and dyscalculic children (Mazzocco, Feigenson, & Halberda, 2011a; Mussolin, Mejias, & Noel, 2010; Piazza et al., 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007). However, because correlations do not prove causation, to date we have no definitive proof of a causal link between the ANS and math proficiency. The ANS may play a causal role in determining later proficiency in mathematics at school, but, conversely, the cultural acquisition of symbolic numbers and arithmetic may also enhance ANS acuity (Mussolin et al., 2010; Piazza et al., 2010). This circular causality pattern also affects the reading domain, where phonological abilities determine reading competence but is also improved by literacy (Bradley & Bryant, 1983; Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Morais, Cary, Alegria, & Bertelson, 1979).

To partially resolve this issue, we acquired psychophysical measures of ANS acuity in Mundurucu subjects, an indigenous population living in an autonomous territory in Para, Brazil. The Mundurucu language has a very restricted lexicon for number words, and no symbolic system for exact numbers and arithmetic. However, they can perform approximate calculations when dealing with concrete quantities, such as mentally comparing the numerosity of two arrays, or estimating their approximate sum (Pica, Lemer, Izard, & Dehaene, 2004).

Importantly, in recent years, Brazilian education programs have become available to the Mundurucu, but access to them is highly variable across individuals, mainly determined by the proximity of different homes to the few schools. We studied a group of Mundurucu children and adults including individuals who had received no education or some years of schooling. With this unique source of data, we can disentangle the effects of maturation (indexed by chronological age) and of education on ANS acuity.

Our predictions are straightforward. If the observed improvement in ANS acuity with age is solely driven by maturation, then older participants should have a more refined ANS than younger participants, controlling for education level. On the contrary, if ANS acuity is also influenced by educational factors, then educated participants should have a more refined ANS compared to uneducated participants, controlling for chronological age.

METHOD

Main Experiment (Numerosity Comparison)

38 Mundurucu participants were tested (age 4–63, 21 males). Their degree of instruction varied from no schooling up to several years of attendance to the local schools. According to reports from both the Mundurucu school teachers, and the education department at National Indian Foundation (FUNAI), Mundurucu mathematics instruction begins in the third year of formal schooling. During the first year of school (Level 1) pupils learn to speak in Portuguese, and to read/write single letters. During the second year (Level 2) they learn how to read/write words and basic sentences. At the third year (Level 3) numbers and basic arithmetical operations are introduced. The subsequent levels follow the classical Brazilian primary school progression.

Participants reported their school level, which, when possible, was confirmed by school teachers, relatives and village authorities. Of the tested participants, 14 never attended school or only a few months (Level 0), 3 completed school Level 1, 9 Level 2, 6 Level 3, and 6 Level 4 or more.

Stimuli, presented via a solar powered PC, consisted of pairs of arrays of black dots in two white discs on either side of a central fixation. On each trial, one of the two arrays contained either 16 or 32 dots (reference, hereafter n1). The paired array for the reference 16 (hereafter n2) contained 10–22 dots along a 10 levels-continuum, and twice these values for reference 32. Perceptual variables were randomly assigned to each stimulus pair such that, on average, on half the trials dot size of the n2 array was held constant, and on the other half, their total occupied area was held constant; in the n1 arrays, these parameters varied simultaneously (Dehaene, Izard, & Piazza, 2005). Stimuli remained on screen until participants gave their response, consisting in pressing the button on the computer keyboard corresponding to the more numerous set, or pointing towards it, without counting. There were 140 experimental trials, preceded by some training.

Control Experiment (Size Comparison)

We also probed performance in a control size comparison task, during a second mission to the Mundurucu territory. 33 Mundurucu subjects were tested (age 4–67, 20 males). 9 had received no instruction, 5 completed Level 1, 4 Level 2, 6 Level 3, 9 level 4 or more. The experimental structure was identical to the numerosity comparison experiment. Pairs of white discs appeared on either side of a central white fixation spot. Their diameters differed along a continuum spanning the same 10 ratios used for the numerosity experiment. Participants were asked to choose the largest disk button press or pointing. The 140 experimental trials were preceded by some training.

RESULTS

As for Western subjects, Mundurucu psychometric functions were Weberian (sigmoidal once plotted on a log scale of the numerical ratio). Subjects responded within an average of 3.1 seconds (SD = 1.7 secs), incompatible with exact counting.

For each participant, we recovered the Weber fraction (WF) by fitting the 16 and 32 psychometric curves with a single sigmoid function (Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004). Two young participants (aged 5) were excluded after the regression failed to converge, indicating random responses. Our WF measure was reliable (split-half $r = 0.68$, $p < .01$).

The average group WF was 0.25 (range = 0.07–0.45; accuracy = 71%, range = 51–91). We first examined the effect of age and constituted five age groups (figure 1). The WF decreased from 5 to 10 years of age, however, contrary to educated Italian adults, tested in the context of another study using the very same task and stimuli (Piazza et al., 2010), it then ceased to decrease. The mean WF of Mundurucu adults (0.23) was significantly larger than that observed in educated Italian adults (0.15) ($t(38) = 2.95$, $p <.01$)(see figure 2A).

We then used an ANCOVA with age as the covariate and education level as the between-group variable to tease apart the effects of age from those of education on the WF[1]. The effect of education level ($F(7,27) = 3.12$, $p <.05$) accounted for 45% of the WF variance, controlling for age (which effect was marginal ($F(1,27) = 4.04$, $p = .055$))(see figure 2B). We next focused on the adult Mundurucus, for which age and education were best separable: the WF for uneducated subjects was 0.31, twice the value of 0.15 observed in educated Italian adults ($t(25) = 5.12$, $p < .01$), but not different from that of Italian six year-old children ($p = 0.29$) (Piazza et al., 2010). The WF dropped to 0.19 in adult Mundurucus who went to school for at least one year, creating a highly significant difference with uneducated Mundurucus ($t(18) = 2.69$, $p<.05$) (see figure 3), in the context of no age difference ($t(18) = -1.32$, $p = .20$), or in overall RTs ($t(18) = 1.11$, $p = .28$), and no difference from Italian adults ($p = .13$).

The effect of education appears more evident as soon as the school curriculum introduces arithmetic (level 3). Difference contrasts within the ANCOVA confirmed that only at level 3 did the WF become significantly lower than the preceding levels ($p < .01$).

[1]The assumptions underlying the ANCOVA were met: (1) The WF was normally distributed in all education levels (Shapiro-Wilk tests all p's >.05), excluding level 6 and 8, where there was only 1 subject, (2) The variance of the WF did not differ across the education levels (Levene's test $F(7, 28)= 1.380$, $p = .25$), (3) The slopes of the regression functions relating the WF to age did not differ across the education levels ($F(5,22) = 0.82$, $p =.55$). Results were confirmed by a non-parametric ANCOVA performed on the rank-transformed data (significant effect of education controlling for age $F(7,27)= 3.36$, $p = .01$).

Finally, we explored the effect of language. In our sample, education and bilingualism were highly correlated (r = 0.71), and their effects inseparable. However, for 20 of the 24 monolingual subjects (who could only speak Mundurucu) we knew that they could recite some numbers in Portuguese: 6 subjects could recite numbers only up to "5", while 14 counted at least up to “10”. This difference did not significantly impact on the WF (w = 0.33 and 0.30 for subjects counting only up to 5 those counting up to 10 or beyond; p = .53).

We used a control size-comparison task to verify that education did not impact on all psychophysical tasks. Mundurucu performance consistently varied with the ratio of the sizes, allowing extraction of the WF. On average, the WF was much lower for size (group average = 0.04, range = 0.002–0.10; accuracy = 95%, range = 86–99) than for number, indicating a higher sensitivity to differences in size compared to number. However, the size WF varied importantly across subjects, and decreased throughout the lifespan, starting from 0.059 in children (<10 years), down to 0.029 in older adults (>40 years). We used an ANCOVA with age as the covariate and education as the between-group variable. Contrary to the numerosity task, there was no effect of education ($F(5,26) = 0.77$, $p = .58$) over and above age ($F(1,26) = 3.33$, $p = .08$). Indeed, the size WF was equal for Mundurucu adults with vs. without education (0.033 and 0.034, p = .91). The distinct effects of education on size and number comparison tasks was confirmed by a significant task X education interaction ($F(5,54) = 2.87$, $p < .05$) within an ANCOVA with age as the covariate, and with task and education level as between-subjects variables.

DISCUSSION

By studying a remote Amazonian population, we were separated the effects of education and age on the acuity of the approximate number sense system. These effects are nearly impossible to separate in societies where virtually all children receive an early education in counting and arithmetic. Previous research established that an approximation strategy is available to both Mundurucu and Western subjects. Here we developed a finer-grained measure to quantify its precision at the individual level. The results indicate that education is associated with a significant increase in the acuity of the approximate number system, and does so independently of maturation. Effects of education were observed especially for Mundurucu participants who had advanced far enough in the educational system to receive instruction in symbolic enumeration and arithmetic.

In members of industrialized societies, the developmental trajectory of the ANS is characterized by an initial sharp improvement followed by a progressively smaller but long-lasting change (Halberda & Feigenson, 2008; Piazza et al., 2010). While the initial ANS improvements likely reflect intrinsic maturational and sensory factors, the present data suggest that the later ANS improvements are almost entirely imputable to education: in Mundurucu subjects not exposed to formal education, number acuity ceases to increase beyond the level reached by North American and European children at about 6 years of age, around the time when formal schooling starts.

The Weber fraction of the uneducated Mundurucus (0.31, twice the value observed in educated adults) is also comparable to the Weber fraction of a group of Italian dyscalculic children (0.35) tested with exactly the same experimental paradigm and procedure (Piazza et al., 2010). This suggests that the impairment in the Weber fraction in dyscalculics (Mazzocco et al., 2011a; Mussolin et al., 2010; Piazza et al., 2010; Price et al., 2007) may be partially a consequence of poorer school-based acquisition of numeracy. Such an educational “confound” may well apply to other studies reporting a correlation between the ANS and maths achievement (Halberda et al., 2008; Mazzocco et al., 2011b).

Two observations suggest that the effect of education on ANS acuity is not a generic effect of schooling but a specific effect of numeracy instruction. First, the most significant reduction of the ANS is observed at the level of schooling where the current Mundurucu system introduces counting and the arithmetical operations. Second, education has no effect on a non-numerical perceptual comparison task, suggesting that our results may not be interpreted in terms of improvements of a generic magnitude representation system (Feigenson, 2007; Walsh, 2003), and a fortiori, of a generic schooling effect.

Because the present study did not randomly assign participants to the different groups, however, we cannot completely rule out the possibility that the educated and uneducated subjects differed on variables other than education (even though at the time of testing they had similar occupations and were equally socially integrated). Whether other demographic factors might contribute to the enhancement of the ANS system in educated subjects is a question for future studies. Another important open question is which specific aspects of numeracy influence ANS acuity. Our data suggest that the mere ability to recite the counting list does not suffice to affect the ANS. Longer-term practice with counting, leading to the emergence of a full-blown referential symbolic system (Deacon, 1998), is likely to be necessary to sharpen number sense.

In conclusion, the present study provides evidence that education plays a significant role in sharpening the sense of approximate numerical quantity: number sense is coarser in a culture without symbols for exact numbers, and it becomes more precise in members of that culture who are introduced to the concepts of exact number and calculation.

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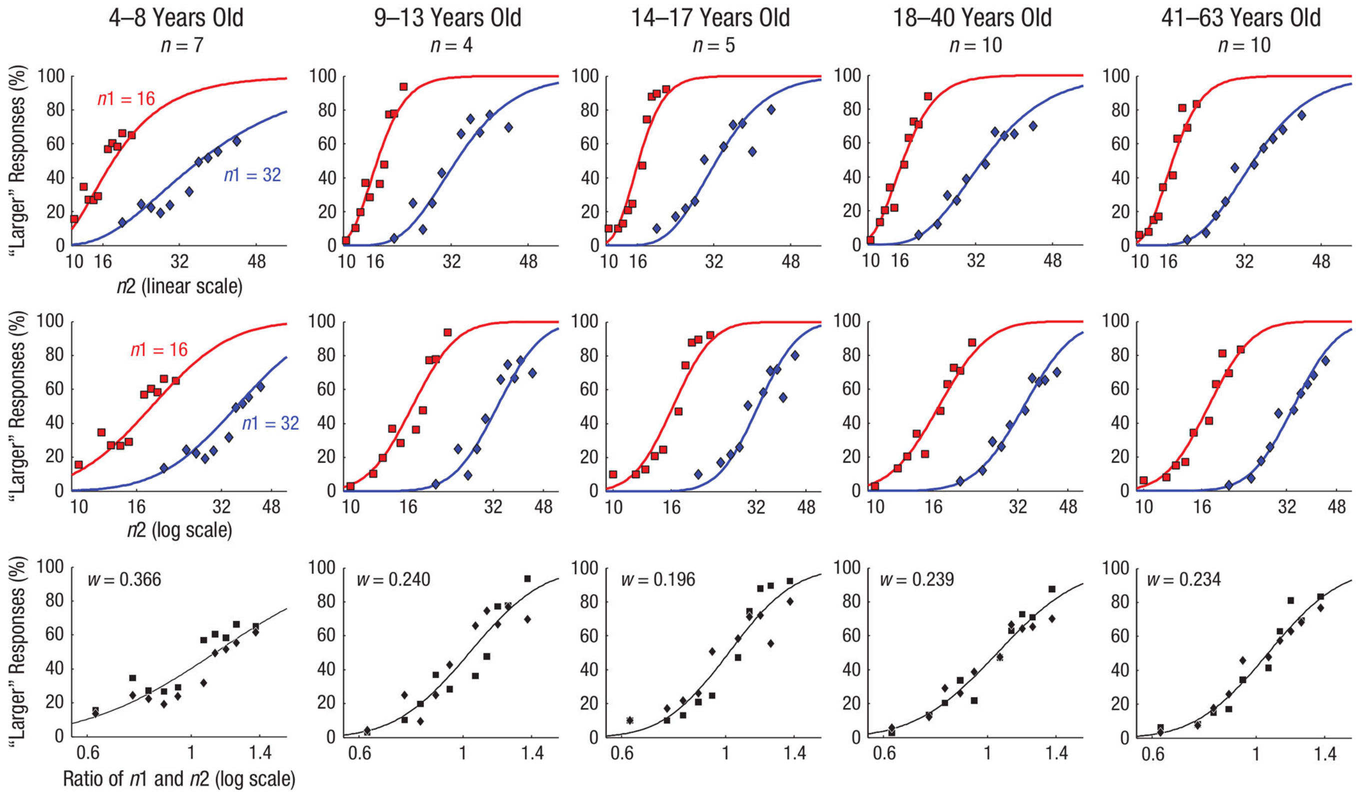

Figure 1. Changes in numerical comparison performance with age

Percent "larger" responses to N2 numerosities are plotted as a function of N1 numerosities (red curve, N1=16; blue curve, N1=32) in Mundurucu subjects grouped in five different age ranges. For all groups, sigmoid fitting functions for the two values of N2 (top row) become parallel when plotted on a log scale (middle row) and superimposable when expressed by the log N1/N2 ratio (bottom row), thus obeying Weber's law.

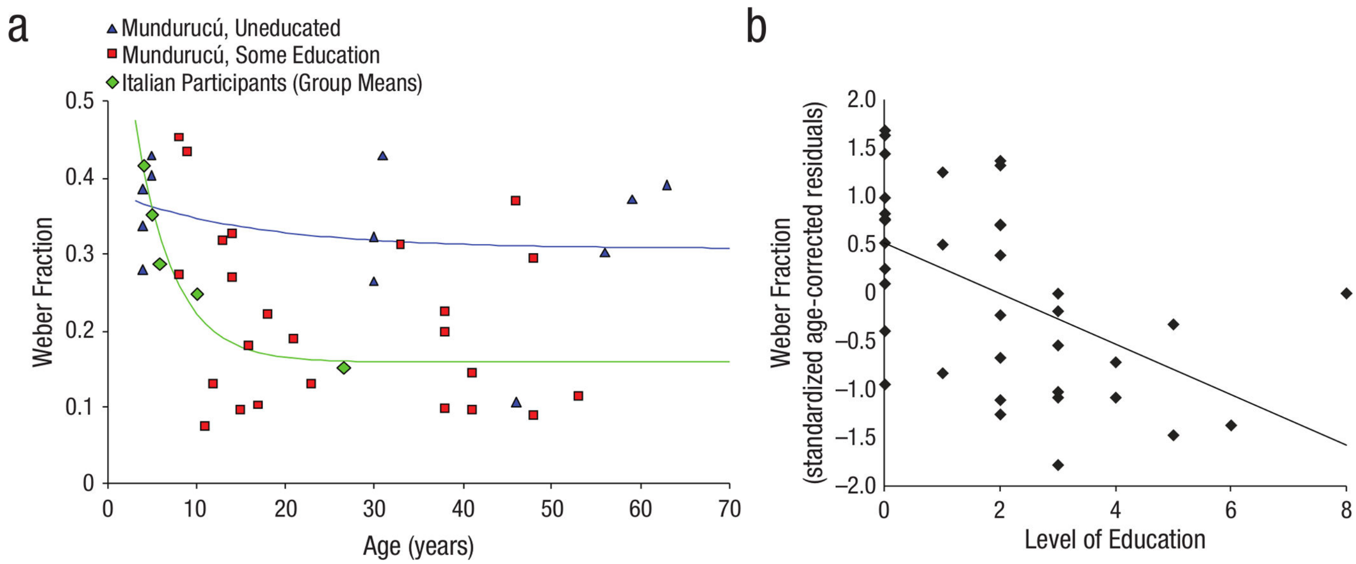

Figure 2. Changes in the Weber fraction with age and education

A, data from individual Mundurucu participants is plotted separately for subjects without education (blue triangles) and with some education (red squares). For reference, green symbols show the evolution of the Weber fraction in 5 groups of Italian participants (4, 5, 6, 10-years old and adults) (Piazza et al., 2010). The fits are decreasing exponentials with a variable decay rate and asymptote. It can observed that the curve derived from Italian participants fits the data from educated Mundurucus, with an initial delay plausibly due to less intense schooling in the Amazon. The performance of uneducated Mundurucus does not seem to develop beyond the 6-year-old level. B, Weber fraction, age-corrected, as a function of education in the Mundurucu. The data suggest that the second-to-third year transition might be a particularly important period for the development of precision in numerical estimation.

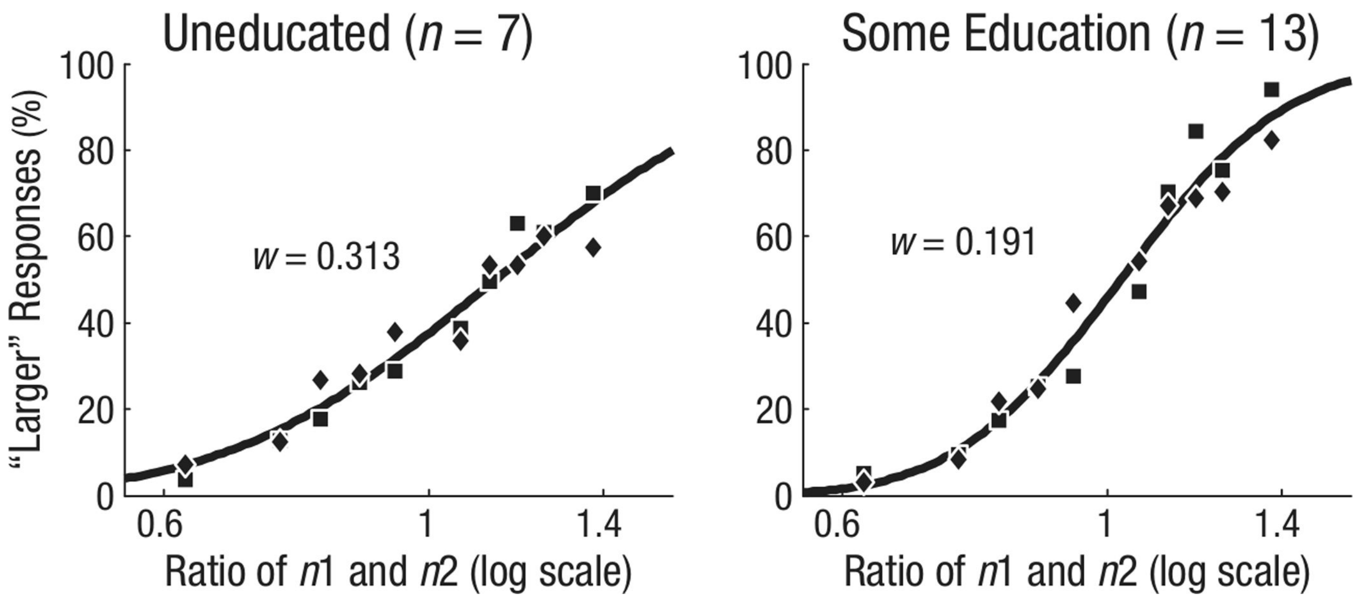

Figure 3. Numerical comparison performance in educated and uneducated Mundurucu subjects