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Differences in the acuity of the Approximate Number System in adults: The effect of mathematical ability

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ABSTRACT

It is largely admitted that processing numerosity relies on an innate Approximate Number System (ANS), and recent research consistently observed a relationship between ANS acuity and mathematical ability in childhood. However, studies assessing this relationship in adults led to contradictory results. In this study, adults with different levels of mathematical expertise performed two tasks on the same pairs of dot collections, based either on numerosity comparison or on cumulative area comparison. Number of dots and cumulative area were congruent in half of the stimuli, and incongruent in the other half. The results showed that adults with higher mathematical ability obtained lower Weber fractions in the numerical condition than participants with lower mathematical ability. Further, adults with lower mathematical ability were more affected by the interference of the continuous dimension in the numerical comparison task, whereas conversely higher-expertise adults showed stronger interference of the numerical dimension in the continuous comparison task. Finally, ANS acuity correlated with arithmetic performance. Taken together, the data suggest that individual differences in ANS acuity subsist in adulthood, and that they are related to mathematical ability.

1. Introduction

Converging evidence indicates that humans possess a system dedicated to extract and represent approximate numerical magnitudes (see Feigenson, Dehaene, & Spelke, 2004, for a review). The Approximate Number System (ANS) is thought to be an innate and universal system, as persons from primitive tribes with a limited set of number words can discriminate numerical quantities (Pica, Lemer, Izard, & Dehaene, 2004), as well as preverbal infants (Xu & Spelke, 2000) and even various non-human animal species (Nieder, 2005). One important question arising from the hypothesis of a biological number perception device concerns its relation with the cultural aspects of mathematical abilities. Several authors have investigated to what extent the ANS and the number knowledge that is acquired at school are related (see Dehaene, 2009, for a review), and studies that focussed on this relationship in adulthood have led to mixed results (Gilmore, Attridge, & Inglis, 2011; Inglis, Attridge, Batchelor, & Gilmore, 2011; Libertus, Odic, & Halberda, 2012; Lyons & Beilock, 2011; Price, Palmer, Battista, & Ansari, 2012). In the present study, we addressed two crucial issues that were not systematically considered in previous work. First, we extended the variation in mathematical ability by sampling adult participants from groups who expressly differ in mathematical ability. Second, in addition to a numerical magnitude comparison task, participants also received a physical (i.e., non-numerical) magnitude comparison task, in order to disentangle specific numerical processes from more general processes involved in the task.

Several studies have emphasized the crucial role that the ANS could play as a cognitive basis for the later acquisition of mathematical knowledge (e.g., Condry & Spelke, 2008; Gilmore, McCarthy, & Spelke, 2007). The innate nature of the ANS makes it a plausible cerebral basis upon which mathematical knowledge is built (Lipton & Spelke, 2003; Xu, Spelke, & Goddard, 2005). This hypothesis is consistent with the general observation that children's ability to manipulate non-symbolic numbers precedes their mathematical instruction (Barth, La Mont, Lipton, & Spelke, 2005). From this view, Halberda, Mazzocco, and Feigenson (2008) hypothesized that the precision of mental magnitude representations could be related to mathematical ability. As expected, they observed that ANS acuity, measured in 14-year-old adolescents, was associated with performance in mathematics throughout their education. Following that study, several authors assessed the relationship between non-symbolic number skills and mathematical ability at early stages of instruction. A significant association was indeed observed in preschoolers (Gilmore, McCarthy, & Spelke, 2010; Libertus, Feigenson, & Halberda, 2011). Further, Mazzocco, Feigenson, and Halberda (2011) found that ANS acuity in preschoolers was predictive of their later mathematical ability in primary school. Thus, from these observations, it seems that the precision of the non-symbolic number representation system at an early stage is related to the acquisition of symbolic

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number knowledge and, by extension, to the acquisition of arithmetic and mathematics skills (but see Iuculano, Tang, Hall, & Butterworth, 2008; Rousselle & Noël, 2007; and Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013, for challenging data).

Although most data in the literature suggest a close association between ANS acuity and arithmetic in childhood, recent studies that investigated this relationship in adults have led to more mixed results. On the one hand, Lyons and Beilock (2011) observed a correlation between ANS acuity and arithmetic performance, and further argued that this relationship was mediated by some symbolic number ability. Their results support the view that symbolic knowledge remains closely related to non-symbolic skills in adulthood. DeWind and Brannon (2012) made a similar observation: they found that the ANS acuity correlated with standardized scores in an arithmetic task, but not with various verbal tests. In the same vein, Libertus et al. (2012) provided further evidence for a specific relationship between ANS acuity and mathematical achievement, independently of any verbal competence. Finally, the close relationship of ANS acuity to mathematics proficiency appears to hold across the lifespan (Halberda, Ly, Wilmer, Naiman, & Germine, 2012). On the other hand, several recent studies did not observe similar relationships between the acuity of the ANS and mathematical ability in adults. Inglis et al. (2011) found a significant correlation between nonverbal numerical skills and mathematical ability in childhood, but they failed to observe the corresponding correlation in adulthood. In the same vein, Gilmore et al. (2011) found that performance in non-symbolic number comparison and addition tasks was not correlated to performance in symbolic number comparison and addition tasks. Finally, Price et al. (2012) made a similar observation that mathematical ability correlated neither with non-symbolic numerical comparison acuity nor with symbolic number comparison acuity. With all these inconsistent results, the view that the link between non-symbolic skills and arithmetic skills remains in adulthood is challenged.

In such a debated context, we aimed to further investigate the relationship between ANS acuity and mathematical ability in adults by examining two issues that might have been insufficiently considered in previous research. A first issue that might explain the inconsistent findings in the literature is the range of mathematics achievement levels in the samples. In fact, except for Halberda et al.'s (2012) study that used a very large sample of participants through the internet, previous studies that focused on adults barely accounted for that point, as they sampled their participants among psychology students (Libertus et al., 2012; Price et al., 2012) or among university students, without further consideration (DeWind & Brannon, 2012; Gilmore et al., 2011; Inglis et al., 2011; Lyons & Beilock, 2011). In the present study, we wanted to address this issue by extending the sampling, among two populations that expressly differ in their mathematical ability to warrant sufficient heterogeneity in mathematical abilities: We indeed sampled participants from a population deemed to be highly proficient in mathematics (i.e., Engineering students), and from a less proficient population (i.e. Psychology students). By doing so we hoped to obtain a sample that would reflect more reliably the heterogeneity of arithmetic achievement levels in educated adults (Geary & Widaman, 1987), as we hypothesized that the higher mathematical ability group would perform better in arithmetic than the lower mathematical ability group.

Another issue that could explain the inconsistencies in previous findings stems from the influence and interference of non-numerical perceptual processes on numerical magnitude judgments in the number comparison task. Gebuis and Reynvoet (2011) recently emphasized that the control of visual cues confounded with numerosity was generally insufficient, and that it is likely that participants weighted the different visual cues to estimate numerical magnitudes (Gebuis & Reynvoet, 2012). From these studies, it seems that other visual (non-numerical) information is extracted in number comparison tasks. Consequently, we wanted to use an appropriate index of sensitivity to number, which would separate specific numerical processing from other, non-specific, components of the task, such as visual perception and magnitude comparison processes. We thus based our methodology on Nys and Content's (2012) study, in which participants had to judge numerical magnitudes in one condition and cumulative area in another condition. In the first condition, the numerical comparison task, participants were asked to determine which of the two dot collections was more numerous; in the other condition, the physical comparison task, they were asked to determine the collection with the largest cumulative area (i.e., a non-numerical dimension). Both tasks used the same set of dot collections in a Stroop-like paradigm. Crucially, Nys and Content not only observed that cumulative area interfered with numerical judgments, but also that numerical magnitude was interfering with area judgments. By using Nys and Content's (2012) paradigm, we would thus be able to dissociate the interference induced by visual cues from the interference induced by numerical processing in the physical comparison task.

Our predictions are straightforward. If a more frequent usage of mathematics in daily life – which is likely to influence arithmetic efficiency – is related to ANS acuity, we should observe a significant correlation between numerical judgment accuracy and arithmetic performance. Furthermore, we hypothesized that adults with high mathematical ability would be more accurate in comparing number magnitudes than adults with low expertise in mathematics. Consequently, we expected that the irrelevant dimension in the magnitude judgment tasks (either numerical or physical) would affect differently the performance as a function of mathematical ability: Math-efficient adults should be more influenced by the numerical dimension in the physical comparison task, while adults with lower mathematical ability should be more influenced by the physical dimension in the number comparison task.

2. Method

2.1. Participants

Fifty-nine students from the Université Libre de Bruxelles (Belgium) participated in the study. Twenty-nine were Engineering students (12 women, mean age, 19.9; 17 men, mean age, 20.7), and the other 30 were Psychology students (15 women, mean age, 18.4; 15 men, mean age, 20.1). All of them were French native speakers and had normal or corrected-to-normal vision. Engineering students were paid and Psychology students received course credits for their participation. We assumed that Engineering students would have higher arithmetic and number skills as they all have to pass an admission examination in mathematics, whereas Psychology students were expected to be less proficient in mathematics and arithmetic as Psychology is part of Human and Social Science curricula in Belgian universities, and is generally seen as requiring only basic mathematical background. Besides, the latter were tested during the first semester, during which they had received no mathematics or statistics course yet.

2.2. Material and procedure

2.2.1. Arithmetic task

Participants had to mentally solve complex additions presented horizontally on a screen. Screen size was 15 in., with a pixel resolution of 1440×900. Every addition contained a pair of two-digit operands (e.g., $49 + 38$). To construct the set of complex additions, we sampled tens and units across all digits, excluding zero and avoiding repetitions of a given digit within a problem. We controlled for the presence of a carry and for the problem size: Half of the additions required a carry to be solved, while the other half did not. Similarly, half the sums were below 100 and half above 100 (mean sum = 91, range = 38–174). The mean distance between the two operands was 19 (range = 5–48). The entire set of stimuli was composed of 96 complex additions.