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Why do we differ in number sense? Evidence from a genetically sensitive investigation☆

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ABSTRACT

Basic intellectual abilities of quantity and numerosity estimation have been detected across animal species. Such abilities are referred to as 'number sense'. For human species, individual differences in number sense are detectable early in life, persist in later development, and relate to general intelligence. The origins of these individual differences are unknown. To address this question, we conducted the first large-scale genetically sensitive investigation of number sense, assessing numerosity discrimination abilities in 837 pairs of monozygotic and 1422 pairs of dizygotic 16-year-old twin pairs. Univariate genetic analysis of the twin data revealed that number sense is modestly heritable (32%), with individual differences being largely explained by non-shared environmental influences (68%) and no contribution from shared environmental factors. Sex-Limitation model fitting revealed no differences between males and females in the etiology of individual differences in number sense abilities. We also carried out *Genome-wide Complex Trait Analysis* (GCTA) that estimates the population variance explained by additive effects of DNA differences among unrelated individuals. For 1118 unrelated individuals in our sample with genotyping information on 1.7 million DNA markers, GCTA estimated zero heritability for number sense, unlike other cognitive abilities in the same twin study where the GCTA heritability estimates were about 25%. The low heritability of number sense, observed in this study, is consistent with the directional selection explanation whereby additive genetic variance for evolutionary important traits is reduced.

1. Introduction

Numbers, in their symbolic notation, form a basic tally system to answer the questions of 'how much' or 'how many'. Numerals are an efficient way to keep track of discrete quantities and numerosities. This is particularly useful if the numerosities to be represented are relatively large. An alternative way to represent quantities and numerosities is to evaluate them in terms of 'more' or 'less'; this approach does not require the use of symbols or any learned system and is based on approximation. The mechanism supporting such approximations, the approximate number system, is also often referred to as 'number sense' (see Dehaene, 1997 for a review). The exact definition and measurement of number sense are often

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debated (see Berch, 2005). This paper will refer to number sense as an intellectual ability that allows us to represent, estimate and manipulate non-symbolic quantities/numerosities. A practical example of using number sense is when, without counting and after a quick glance, we join the queue with the fewest people.

Number sense has attracted considerable attention as individual differences in this ability have been found to be associated with mathematical ability (e.g. Jordan, Kaplan, Oláh, & Locuniak, 2006).

One of the theories underlying mathematical learning is that numeracy skills partially originate from non-symbolic numerosity ability interfacing with the taught symbolic numerical system (e.g. Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004; Izard, Pica, Spelke, & Dehaene, 2008). It has been proposed that deficits in manipulating numerosity are one of the signatures of mathematical difficulties (Butterworth, 1999, 2010; Landerl, Bevan, & Butterworth, 2004; Mazzocco, Feigenson, & Halberda, 2011). There is evidence that symbolic (dealing with numerals) and non-symbolic (dealing with numerosity) number systems contribute interactively to the development of normal arithmetic skills. For example, the native language of a small Amazonian tribe, the Mundurukú, has words for numbers only up to five. Although Mundurukú participants can approximate quantities well above their naming range, they fail to manipulate exact numbers. This indicates that the approximate number system is independent from the verbal encoding of numbers that produces exact numerical representations. Further, if the non-symbolic quantities fail to map onto their symbolic correspondence, the emergence of exact arithmetic may not typically develop (Pica, Lemer, Izard, & Dehaene, 2004).

Some studies, however, challenge the view of a significant relationship between symbolic and non-symbolic representation of numbers. In one study, mathematical achievement in 6-to 7-year-old children correlated with Numerical Distance Effect (speed and accuracy in number comparison are greater when the numerical distance separating two numbers is relatively large, i.e. 3 and 9 vs 3 and 5) in symbolic, but not in non-symbolic comparisons (Holloway & Ansari, 2009). Similarly, children with mathematical disabilities show impairments in comparisons of number symbols, but not in the processing of non-symbolic numerical magnitudes (Rousselle & Noël, 2007).

1.1. Numerosity discrimination in animals and humans

The approximate number system is not unique to humans. Many animal species can approximate numerosities and can remember discrete number of objects and events. Basic numerical competences have been reported in social and non-social animals (ants: Reznikova & Ryabko, 2011; bears: Vonk & Beran, 2012); mosquito fish discriminate quantities using numerical cues and can be trained to recognize a set of two items from another with three (Agrillo, Dadda, Serena, & Bisazza, 2009; Agrillo, Piffer, & Bisazza, 2011); and rats can distinguish between arrays with different numbers of auditory signals (Meck & Church, 1983). In addition to estimation abilities, rudimentary arithmetic skills performed on numerosity sets (i.e. collection of discrete items) have been reported by studies that used attachment paradigms with newborn chicks (Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009; Rugani, Regolin, & Vallortigara, 2011).

Animal evidence suggests that basic numerical competences are independent from language and are present at birth. Studies of human infants also show that this ability is preverbal. Using habituation paradigms it has been shown that babies as old as 6 months are able to distinguish between arrays of items or sequences of sounds of 4 from 8, and 8 from 16 (ratio 1:2) (Lipton & Spelke, 2003; Xu & Spelke, 2000). Older babies can discriminate between finer ratios. At 9 months for example, babies can discriminate between displays of 8 and 12 items (ratio 2:3) (Lipton & Spelke, 2003) and between the age of 3 and 6 years, children can distinguish between ratios of 3:4 and 5:6 (Halberda & Feigenson, 2008). In adulthood, estimation skills peak, allowing discrimination between arrays with ratios of 9:10 (Halberda, Mazzocco, & Feigenson, 2008; Pica et al., 2004).

Such evidence from animal and infant studies suggests that basic estimation skills involved in number sense are evolutionarily conserved. However, this does not imply that individual differences in number sense are genetic in origin. Behavioural genetic studies have shown that in almost every aspect of human behaviour and cognition, individual variation is a product of both, environmental and genetic influences (Plomin, DeFries, Knopik, & Neiderhiser, 2012). Genetic influences on individual differences in a trait in a particular population are called heritability. Therefore, heritability does not refer to the genetic effects on the presence of a function (e.g. human ability to learn new information), but to the proportion of the variance in this function (e.g., people have different learning capacities) that can be explained by variance in human DNA.

Evidence from both animals and humans suggests that for morphological traits (e.g. weight, body size, height), individual differences are under stronger genetic influence than for fitness-related traits (e.g. fertility, longevity) (Visscher, Hill, & Wray, 2008). In other words, for traits that have a clear positive end on a continuum (the healthier — the better) vs. no clear positive end (not the taller the better), evolution is less permissive of genetic variability. If number sense is of primary importance for survival for many species, it is more likely that genes will not play a large role in determining individual differences in this ability. A similar example is attachment – an important evolutionarily preserved trait in mammals – which shows low heritability, suggesting that individual differences in attachment are largely a product of environmental influences (Plomin et al., 2012). Because directional selection depletes additive genetic variance (genetic effects that add up across genes and are inherited from parent to offspring), traits subjected to selection pressure would be expected to show lower heritability. To date, nothing is known about the relative contribution of genetic and environmental factors to the substantial variability in numerosity discrimination documented by previous research, reviewed in the following section.

1.2. Individual differences in numerosity discrimination

One fundamental parameter in estimation skills, used to assess an individual's number sense acuity, is the ratio of the items in the arrays that are being compared. Discrimination