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Letter

Number Faculty Is Rooted in Our Biological Heritage

Andreas Nieder[1,*]

'Is there really an evolved capacity for number?' The answer to the title question of Núñez's [1] opinion article is a clear 'yes', despite his attempts to demonstrate otherwise. Only argumentation based on biological misconceptions and a downplay of empirical data can lead to the assumption that our symbolic number capacity is a purely cultural invention.

The symbolic number faculty cannot be reduced to simply a product of culture. The brain, a biological organ with a genetically defined wiring scheme and predetermined flexibility, is predisposed to acquire a number system. Culture can only shape our number faculty within the limits of the capacities of the brain. Without this predisposition, number symbols would lie beyond our grasp. How proficiently – or even if – we learn to deal with a number system is influenced by culture [2]. However, because the brain gives rise to our number competence, a cultural number faculty (or any fundamental capability) detached from the constraints of the brain is inconceivable.

Our brain has been shaped by selection pressures during evolution. Therefore, its key faculties – in no way as trivial as snowboarding [1] – are also products of evolution; by applying numbers in science and technology, we change the face of the earth and influence the course of evolution itself. The faculty for symbolic number cannot be conceived to simply 'lie outside of natural selection' [1]. The functional manifestations of the brain need to be adaptive because they determine whether its carrier survives to pass on its genes. Over generations, this modifies the genetic makeup of a population, and this also changes the basic building plan of the brains and in turn cognitive capabilities of the individuals of a population. The driving forces of evolution are variation and natural selection of genetically heritable information [3]. This means that existing traits are replaced by new, derived traits. Traits may also shift their function when the original function becomes less important, a concept termed 'exaptation' [4]. In the number domain, existing brain components – originally developed to serve nonverbal quantity representations – may be used for the new purpose of number processing [5,6].

The statement that our brain is equipped with a number faculty that has been shaped by evolution does not bear any teleological connotation, as Núñez [1] implies. It simply states a fact. There is no goal, no *telos*, in evolution. Exactly as it was never a goal to give rise to dinosaurs, there was never a goal to have a species endowed with symbolic systems. But here is the interesting aspect: it did happen! – and this requires a scientific explanation which Núñez's [1] proposal cannot offer.

Fortunately, and contrary to Núñez's [1] rendition, it has been recognized that numerical cognition, both nonsymbolically and symbolically, is rooted in our biological heritage as a product of evolution [7]. The explanatory value of this insight is tremendous. It can explain why we see evolutionary relationships of numerical skills between animals and ourselves. While wild animals spontaneously use numerical information to arrive at informed decisions, trained animals show us the scopes and limits of their numerical competence under stimulus control and high motivation. The combination of controlled behavioral tasks in animals with the simultaneous recording of neural activity presents a unique opportunity to explore the neural basis of brain functions for number. The evolved capacity for number lets us comprehend why we start out with a nonsymbolic numerical toolkit early in life that predicts later mathematical performance [8]. We get an idea of how hunter-gatherer societies with a very restricted range of number symbols represent numerical information and how culture may bring about conceptual changes in numerical understanding [9]. Recognition of an evolved number system is particularly indispensable in relating brain and cognition. It explains why the core brain areas recruited for numerical quantity are equivalent in humans and nonhuman primates, and why numerical selectivity is present irrespective of training or explicit numerical tasks [7]. Such 'number neurons' represent numerical information in the same way as 'place cells' encode allocentric location and 'time cells' represent temporal intervals [10]. Moreover, the brain mechanism of numerosity extraction seems to be functional before symbolic education in preverbal children, and is related to abilities observed in the primate lineage. Finally, damage to brain areas hosting numerical information causes counting and calculation deficits, and developmental deviations of these brain networks for number are responsible for low numeracy in dyscalculia [11].

Our faculty for symbolic number, no matter how much more elaborate than the nonsymbolic capacity of animals, is part of our biological heritage. This insight provides an unprecedented scientific explanation of how we arrive at and grasp numbers. Exactly paralleling the faculty of language [12], the number faculty emerges from biological systems, and it therefore carries biological characteristics.

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Letter

Number – Biological Enculturation Beyond Natural Selection

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Is there a biologically evolved capacity specific for number? [1]. I say 'no' because crucial biocultural phenomena necessary for the realization of exact symbolic quantification – number – occur outside the realm of natural selection [1]. In his comment, Nieder, whose work on the neural underpinnings of quantity encoding I have long admired, answers with a 'clear "yes"' [2]. Our diametrically opposed answers stem from fundamentally different views of the crucial concepts at stake: 'human evolution', 'culture', 'number', and 'symbolic reference'.

I agree with Nieder that 'a cultural number faculty . . . detached from the constraints of the brain is inconceivable' [2] and have explicitly argued accordingly elsewhere [3,4]. I even agree with Nieder's title that 'number faculty is rooted in our biological heritage' [2]. 'Rooted', however, is a vague term that does not allow for scientific clarity. Worse, if by 'biological heritage' what is meant is 'natural selection alone', then it is deeply misleading. Indeed, snowboarding [1] can be said to be 'rooted in our biological heritage' because it builds on biological functions such as bipedal action, balancing, and optic-flow navigation. Despite being made possible by processes in human evolution, snowboarding is obviously not the result of natural selection alone. Conceptual and terminological accuracy are needed to understand the emergence not only of snowboarding but also of exact symbolic quantification, namely, number.

Yes, the driving forces of evolution are variation and natural selection of variable genetically heritable traits [5]. However, Nieder's view of human evolution is too simplistic. In complex organisms like humans that is not all there is. As the prominent geneticist and evolutionary biologist Theodosius Dobzhansky put it: 'Human evolution has two components, the biological or organic, and the cultural or superorganic. These components are neither mutually exclusive nor independent, but interrelated and interdependent. Human evolution cannot be understood as a purely biological process, nor can it be adequately described as a history of culture. It is the interaction of biology and culture' ([6], p. 18). Contrary to Nieder's characterization, which leads him to misattribute to me the claim that 'our symbolic number capacity is a purely cultural invention' [2], culture does not operate detached from biology. Biology constrains cultural changes, and, in turn, culture constrains biological changes such that human cultural practices can even modify the very human genome. For at least 7000 years 'cultural traits' such as animal domestication and adult milk consumption produced strong selective pressure that led to lactase persistence in adults in two independent groups in Africa and Europe [7]. Importantly, however, such cultural traits go beyond 'exaptations' [8] that Nieder mentions. Although exaptation provides flexibility to the evolution of lineages, it still operates within the strict boundaries of natural selection and genetically heritable information. Cultural evolution, by contrast, transcends the strict vertical generational boundaries of natural selection. Not only can cultural traits be 'passed on' via enculturation to genetically unrelated individuals, but these also can be passed in all directions – horizontally to peers, and even 'backwards' to older generations. This extra flexibility, operating outside of natural selection, allows the passing on of a peculiar cultural trait: the concern with a generalized exact symbolic quantification – number.

Although ubiquitous today in the industrialized world, general exact quantification is not universal among humans: for example 85% of nearly 200 languages from Aboriginal Australia surveyed do not have numerals beyond 'five' [9]. Inconsistent with Nieder's argument, language is indeed universal in humans, but general exact quantification – number – is not. To take numbers as pregiven evolutionary explananda constitutes, despite Nieder's claims to the contrary, a classic teleological move. Evolutionary arguments should seriously consider the wide range of human quantity-related practices, and deemphasize the inexact and non-symbolic feats and limitations manifested in nonhuman animals.

Undeniably, humans and other species have some biologically endowed capacities for discriminating quantities. Nevertheless, to over-inclusively label all of them as 'numerical' blurs important distinctions and facilitates teleological arguments. In the name of scientific clarity I proposed to at least disentangle the inexact and non-symbolic treatment of quantity from the exact and symbolic one – labeled quantical and numerical,