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Research Focus

Adding up the effects of cultural experience on the brain

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How does the brain represent number and perform mathematical calculations? According to a recent and provocative study by Tang and colleagues, it depends on which language you learn. They found that the divergent linguistic and cultural experiences of native Chinese and native English speakers are associated with distinct patterns of brain activity during mathematical processing. Their results raise important questions about the cognitive and neural specificity of cultural influences on mathematical processes and the core nature of mathematical cognition.

Introduction

Individual experience can exert a powerful influence on the functional anatomy of the brain. For instance, amputees who have lost a limb do not maintain a defunct representation of the limb in the somatosensory cortex; instead that area of the brain becomes responsive to adjacent, intact skin areas [1]. Remarkably, alterations to the source and nature of cortical input can result in adaptive functional changes to the brain. However, other aspects of brain function are resistant to the influence of experience. For example, language comprehension activates the same network of left hemisphere brain regions regardless of whether language is spoken and heard (by hearing individuals) or signed and seen (by deaf individuals). Thus, in some cognitive domains, dramatic differences in experience produce parallel changes in brain function, whereas, in other domains, dramatic differences in experience have little effect on brain function. A recent study by Tang and colleagues [2] suggests that different cultural experiences can induce variation in brain function during mathematical problem solving. Their report provides exciting new evidence that culture and language structure the brain.

Tang *et al.* [2] performed functional magnetic resonance imaging (fMRI) on native Chinese and native English speakers while they performed four tasks. Three tasks involved Arabic numerals: a font-matching task, a number-comparison task and an addition task. In the fourth task, which paralleled the numerical font-matching task, participants reported whether three nonsense shapes were italicized or upright. For Chinese and English speakers, all four tasks recruited a common occipitoparietal network. However, a cultural dissociation emerged for the numerical conditions, wherein English speakers showed greater activity than Chinese speakers in left perisylvian language areas but Chinese speakers showed greater activity than English speakers in the premotor cortex (Figure 1).

Tang *et al.* offer a few explanations for this cultural dissociation in mathematic-related brain activity. For example, they suggest that enhanced premotor activity in Chinese speakers relates to the greater visuospatial demands of Chinese reading and writing systems. Furthermore, they propose that the greater perisylvian activity in English speakers might be related to a known disadvantage in working-memory efficiency for processing number symbols in English speakers compared with that in Chinese speakers. Although this report establishes that some aspects of Chinese- and English-speaking cultures lead to neural differences in mathematical processing, the data kindle further discussion about the exact nature of this cultural dissociation. Namely, which specific aspects of culture result in the observed patterns of brain activity for Chinese and English speakers?

The cultural divide

Although formal abacus instruction is not emphasized in modern Chinese schools, it remains an important difference between the mathematical practices of native English and Chinese speakers. Children who receive abacus training mentally visualize and manipulate abacus beads to solve mathematical problems. By 11 years of age, masterful abacus users can add together five three-digit numbers in about three seconds [3]. Such expertise could lead to quantitative or qualitative differences in the brain processes that underlie mathematical performance. Abacus imagery might increase the speed and efficiency of solving mathematical problems. Alternatively, abacus imagery might recruit cognitive and neural processes that are not otherwise used for mathematics. Indeed, prior studies indicate that, unlike their non-expert peers, Chinese children who have abacus expertise activate visuospatial circuits during addition tasks that contain Arabic numerals [4]. Thus, different patterns of brain activity can emerge during mathematical tasks even among individuals from the same culture who share the same language.

Notwithstanding abacus experience, Chinese-speaking children typically outperform their English-speaking peers when performing mathematical tasks. Different levels of achievement are likely to be caused by greater rigor in the Chinese mathematical curricula compared with that in English-speaking cultures. Yet, differences in the linguistic structure of Chinese and English counting systems also affect mathematical performance. In particular, the linear transparency of the Chinese counting system enables

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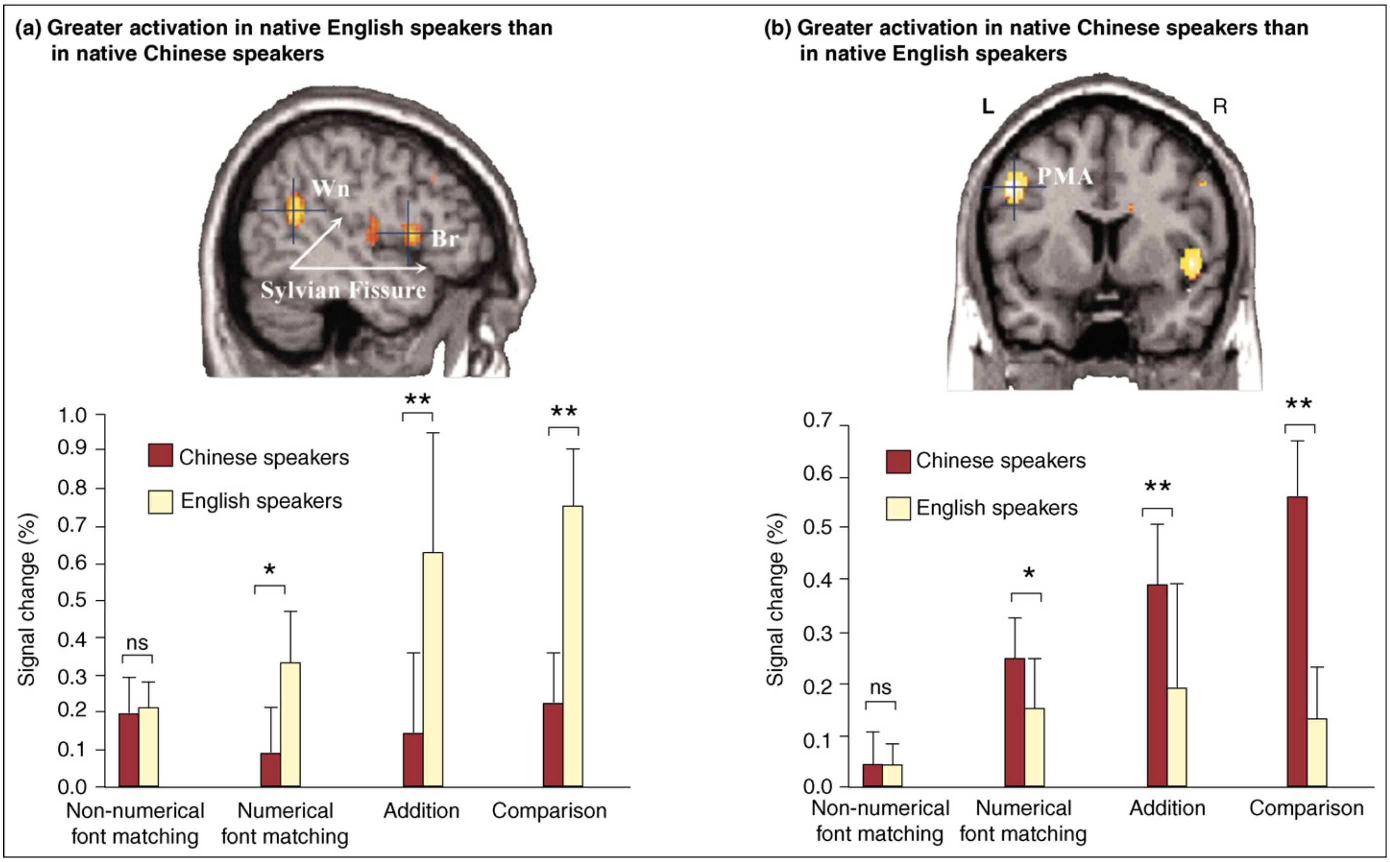

Figure 1. Native Chinese and English speakers exhibited distinct patterns of brain activity during mathematical tasks. **(a)** English speakers produced significantly greater activity in Wernicke's area (Wn) and Broca's area (Br) during the three numerical tasks (numerical font matching, addition and comparison) but not during the non-numerical task (non-numerical font matching) that required orientation judgments of nonsense shapes. **(b)** By contrast, the premotor cortex of native Chinese speakers showed greater activity, specifically the 'premotor association area' (PMA), than did the premotor cortex of native English speakers during the three numerical tasks. Figure reproduced, with permission, from Ref. [2].

Chinese-speaking children to learn the names of large numbers more rapidly than English-speaking children are able to [5]. Because Chinese- and English-speaking children differ in verbal numerical performance even before schooling begins, different patterns of mathematic-related brain activity might originate early in development. A developmental analysis of mathematic-related brain activity in Chinese and English speakers who have different levels of competence in abacus practice and verbal counting would enable a more direct assessment of the contributions of these factors towards differences in mathematical processes.

Individual differences in mathematical strategies might also lead to variability in brain activity. Substantial evidence indicates that the strategies people use to perform mathematical tasks vary. For example, native Chinese-speaking graduate students and native Canadian (English- and French-speaking) graduate students rely on different cognitive procedures for addition and subtraction [6]. Although mathematical strategies can be divided along cultural lines, they also vary within cultures [7]. Therefore, one possibility is that the variability in brain activity observed by Tang *et al.* occurs among individuals from the same culture who use different mathematical strategies. Conversely, Chinese and English speakers might exhibit similar patterns of brain activity during mathematical tasks for which they are known to use the same strategy, such as multiplication [6].

It will be essential for future studies to assess the role of general cognitive functions in culture-specific patterns of brain activity. The global features of Chinese and English languages are different. Chinese characters are logographic, representing whole words, unlike alphabetic English characters. Chinese characters are also orthographically unique; they are high in visual complexity and consist of multiple nonlinear strokes. Accordingly, Chinese and English speakers exhibit differences in brain activity during written language processing [8]. When reading Chinese or English, bilingual native Chinese speakers show increased activity in the left middle frontal gyrus, adjacent to premotor cortex, whereas native monolingual English speakers do not. Therefore, broad differences in reading processes might trigger distinct neural processes in Chinese and English speakers during many tasks.

In addition, working-memory capacity for numbers is greater in Chinese speakers than in English speakers. The Chinese digit-span advantage is thought to result from the brevity of Chinese number words relative to English number words [9]. Differences in working memory are also known to affect the efficiency of mathematical-fact retrieval in Chinese and English speakers. Reduced efficiency in working memory could lead to greater, more sustained or strategically different recruitment of working-memory resources during mathematical tasks in English-speaking subjects and, consequently, greater activity in perisylvian brain regions [10].

To summarize, Chinese- and English-speaking cultures differ in their writing systems, abacus practice, working memory for numbers and in their preferred mathematical strategies. The task now is to determine which, if any, of these cognitive and neural differences between Chinese and English speakers are central to mathematical functioning and which are peripheral. A crucial test of the centrality of these cultural differences will be to determine their effect on the core properties of numerical cognition.

The common denominator

Some aspects of numerical cognition could be impervious to the influence of culture and language. Before infants can talk, they represent numerical values and perform basic arithmetic computations on these quantities [11]. Likewise, non-human animals represent numerical values nonverbally and perform numerical computations [12]. Despite complex symbol-based systems for manipulating numbers, adult humans also possess a nonverbal numerical system that has the same behavioral signatures as that of animals and preverbal humans. When adults

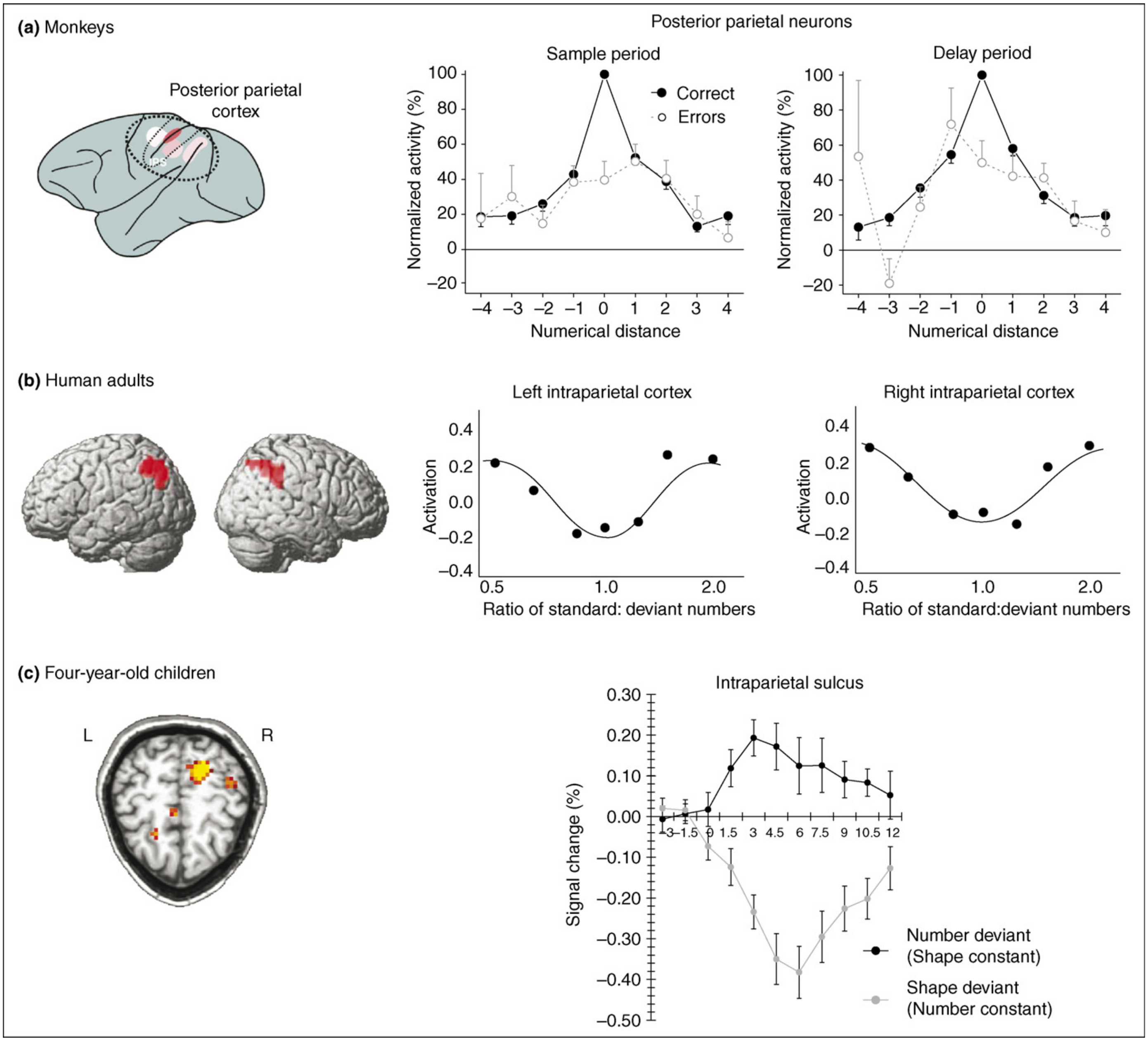

Figure 2. Monkeys, human adults and young children recruit homologous regions of parietal cortex during numerical processing. **(a)** Single neurons in the posterior parietal cortex, including the intraparietal sulcus (IPS), respond to numerical values in macaque monkeys who are trained in a delayed numerical-matching task with arrays of dots. During both the sample and delay periods of numerical-matching trials, single neurons respond maximally to a preferred numerical value (0 point on the *x*-axis) and their response decreases as the numerical value tested increases or decreases in value from the preferred numerical value. Reproduced, with permission, from Ref. [15]. **(b)** In an fMRI-adaptation paradigm, adult humans repeatedly presented with visual arrays containing the same number of elements (standard number) exhibit increased activation in the intraparietal cortex when a novel number of elements is presented (deviant number). The level of activation is modulated by the ratio between the standard and deviant numbers such that activity increases as the deviant number becomes more divergent from the standard number. Reproduced, with permission, from Ref. [14]. **(c)** Similarly, four-year-old children who are repeatedly presented with visual arrays of dots containing the same number of elements of the same local element shape produce an increase in activity in the IPS when presented with a novel number of dots (number deviant), even when element shape remains constant. By contrast, activity in this region decreases when arrays are presented with no change in number, despite changes to the element shape (shape deviant). Reproduced, with permission, from Ref. [13].

quickly compare visual arrays based on number, without verbally counting, their performance is virtually indistinguishable from that of monkeys [12].

It also seems that the neural basis of nonverbal number processing is relatively constant across species and throughout development (Figure 2). By four years of age, English-speaking children exhibit similar patterns of brain activity in the posterior parietal cortex to that in adults when processing non-symbolic numerical values [13,14]. Moreover, neurons in homologous parietal regions encode number in rhesus monkeys [15]. In short, posterior parietal regions of the brain seem to have deep evolutionary and developmental roots in aspects of non-symbolic numerical processing.

The neural correlates of these non-symbolic numerical abilities are distinct from those of language-dependent mathematical thinking. For example, when adults solve precise, symbolic mathematical problems, their performance is encoded linguistically and engages left inferior frontal regions that are active during verbal tasks [16]. These language-related areas are not reported to be active in neuroimaging studies of non-symbolic number processing. It seems likely, then, that only language-dependent mathematical structures are modified by cultural differences. As such, we predict that the functional neuroanatomy of non-symbolic number processing does not differ between Chinese and English speakers.

Summing up

Tang and colleagues [2] demonstrate that Chinese and English speakers recruit different cortical networks to solve the same mathematical problems. This observation provides key evidence that cultural experiences shape brain functions. An important next step is to identify the driving force behind this cultural dissociation. However, regardless of the nature of this cultural effect, it seems unlikely that all mathematical cognition is malleable to the influence of culture. Instead, it is likely that the neural circuits that process approximate numerosity in preverbal infants, non-human animals and adults cannot be changed by cultural and linguistic experience. Written language and complex cognitive strategies are defining features of human development. By deliberately examining the impact of these cognitive innovations on neural systems, future research should shed light on the ways in which culture can and cannot transform the mathematical brain.

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Letters

Using multi-voxel pattern analysis of fMRI data to interpret overlapping functional activations

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Norman *et al.* [1] recently reviewed the use of multi-voxel pattern analysis (MVPA) of fMRI data. They provided examples that showed that patterns of activation across a set of voxels can contain far more information about mental states than the more typically used univariate approach. Patterns of fMRI activation can be used to discriminate cognitive states (sometimes called 'mind

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