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CHAPTER 10

Numbers in the cultural brain

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Abstract: Recent functional neuroimaging studies have indicated that culture may contribute to differential representation of Arabic numbers in the brain of Chinese and English speakers. The brain networks underlying even very simple arithmetic operation differ among these groups. To what extent do different cultures lead to differences in functional connectivity among the distributed brain areas that constitute the network supporting numerical and arithmetic processes? Key cultural differences are educational system, learning strategy, reading experience, and even genetic background; which ones are important? This review addresses these questions and summarizes findings from recent research on number/arithmetic cognition as well related studies in other cognitive domains. Future directions are also addressed.

Keywords: Arabic numbers; fMRI connectivity; cultural influences

The universal use of Arabic numbers in mathematics raises the question whether they are processed the same way in people of different cultures and languages, such as Chinese and English. To address this question, we used functional magnetic resonance imaging (fMRI) to scan 12 native Chinese speakers (NCS) and 12 native English speakers (NES) with college-level education. The subjects were instructed to perform four tasks during the scanning: (i) *Symbol*: Judgment of the spatial orientation of nonnumerical stimuli in which a triplet of nonsemantic characters or symbols was visually presented either in an upright or in an italic orientation; the task was to decide whether the third symbol had the same orientation as the first two. (ii) *Number*: Judgment of the spatial orientation of numerical stimuli (the task was the same as the *Symbol* condition except for using Arabic digits as visual stimuli). (iii) *Addition*: The numerical addition task was to determine whether the third digit was equal to the sum of the first two in a triplet of Arabic numbers. (iv) *Comparison*: The quantity comparison task was to determine whether the third digit was larger than the larger one of the first two in a triplet of Arabic numbers (see Fig. 1 for examples). A baseline condition of matching white and/or gray circular dots was used to control the motor and nonspecific visual components of the tasks.

Our results indicated a differential cortical representation of numbers between NCS and NES. While the English speakers were found to employ a language process relying on the left perisylvian cortices for mental calculation such as a simple addition task, the Chinese speakers,

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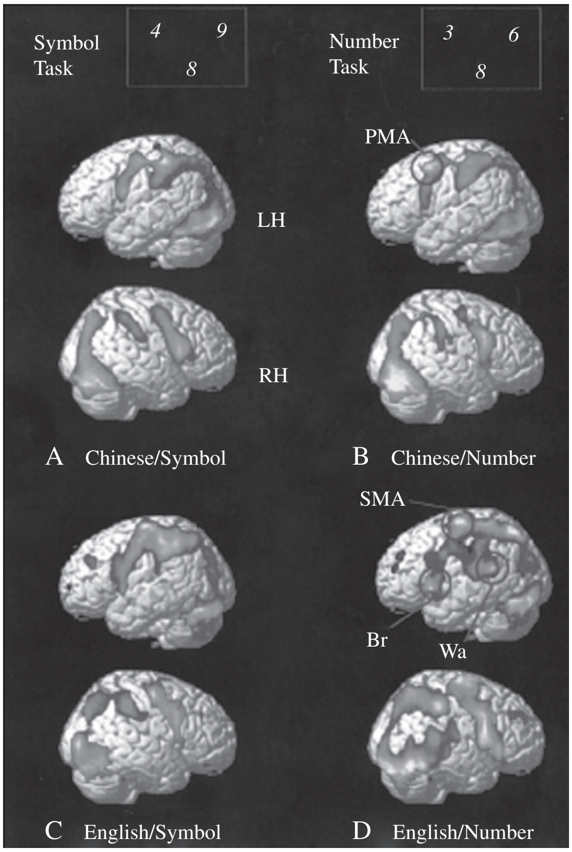

Fig. 1. Dissociation in the brain representation of Arabic numbers between NCS and NES. (A) During the Symbol task in NCS. (B) During the Number task in NCS. (C) During the Symbol task in NES. (D) During the Number task in NES. The task-dependent brain activation was determined by SPM99 by using a liberal threshold ($P<0.05$) for illustrating a global pattern of the fMRI BOLD signal changes. Type-I error of detecting the differences was corrected for the number of resolution elements at each of the activated brain regions defined anatomically by using the SPM add-on toolbox AAL. The *multiple comparison correction* is the small volume correction (SVC) procedure implemented in SPM. (A and B) Examples of the visual stimuli used for the Symbol and Number tasks, respectively, are shown at the top. LH, left hemisphere; RH, right hemisphere; Br, Broca area.

instead, engaged a visuo-premotor association network for the same task (Tang et al., 2006).

We further chose two regions of interest (ROI) in the perisylvian language region, including both the Broca and Wernicke areas, and in the premotor association area in between BA6, BA8, and BA9 for quantitative analyses by comparing the fMRI signal between the English and Chinese groups. We found the perisylvian activations are significantly larger in the English speakers than in the Chinese speakers (Fig. 2A). As the arithmetic loading increased across all of the four conditions (*Symbol* < *Number* < *Addition* < *Comparison*), there was a trend of increase in the premotor activation in the Chinese speakers but not in the English speakers (Fig. 2B). Therefore, between these two groups, there was a double dissociation in the brain activation during these tasks, supporting clear cultural differences in processing of number.

In both groups the inferior parietal cortex was activated by a task for numerical quantity comparison; however, the ROI-based functional MRI connectivity analyses (He et al., 2003) revealed a distinction between Chinese and English groups among the brain networks involved in the task. In the numerical comparison, two distinct patterns were shown in the functional networks (Fig. 3B and D), in which there was dorsal visuo-pathway dominance (through the parietal–occipital cortex) for the Chinese speakers, but ventral visuo-pathway dominance (through the temporal cortex) for the English speakers.

Our findings have two implications. First, in both Chinese and English speakers, there is cortical dissociation between addition and comparison processing. The addition task seems more dependent upon language processing than the comparison task, which is consistent with the suggestion that there are differential neural substrates underlying verbal and numerical processing (Dehaene and Cohen, 1995; Dehaene et al., 1999). Second, there are differences in the brain representation of number processing between Chinese and English speakers. These two different cultural systems may shape the process of Arabic digits differently. These findings might be due to differences between the two cultures in languages, in educational systems, or in genetics. We discuss each of them in the following sections.

Language

Language would be expected to matter more in the addition task than in the comparison task. If so, why during comparison are there much

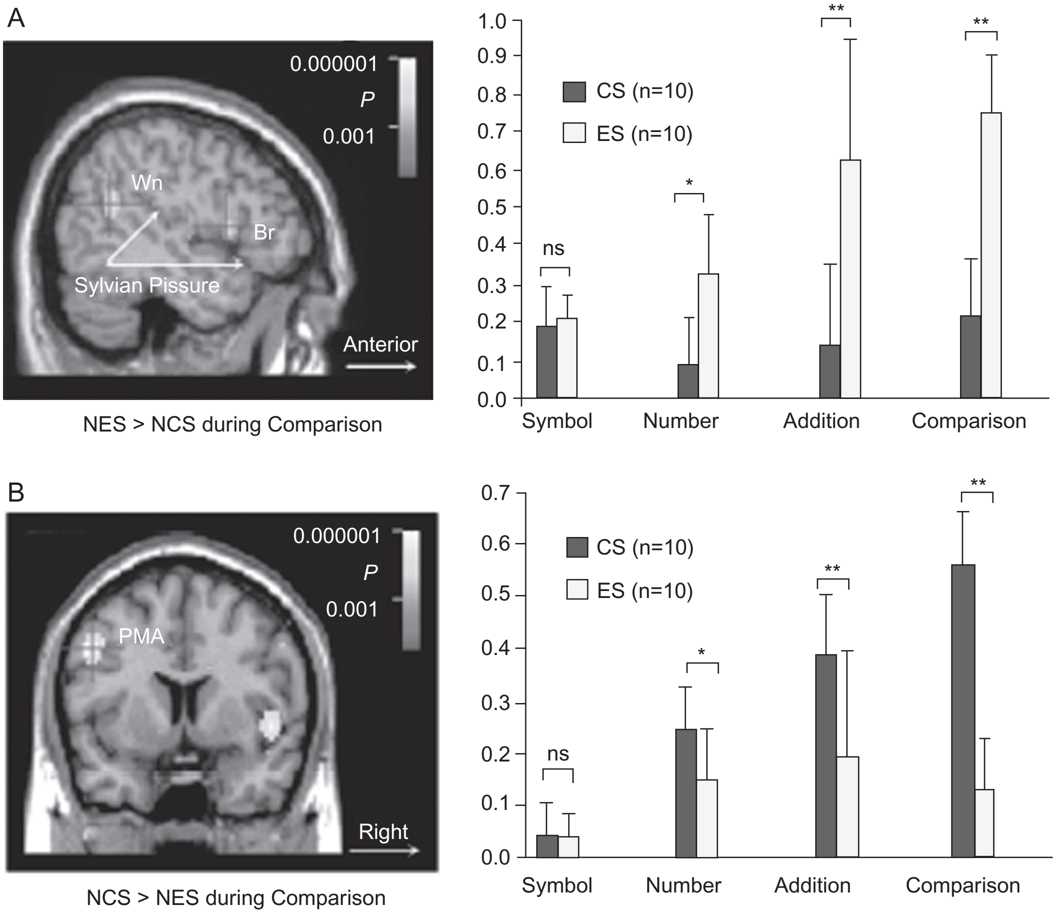

Fig. 2. Comparison of the activation intensity between NCS and NES in the perisylvian language region (A) and the PMA (B). The brain activation maps (left) were determined by contrasting BOLD signal between NCS and NES only during the Comparison task, with the NES group showing relative increase of the signal (A, English > Chinese) and the NCS group showing relative increase of the signal (B, Chinese > English). The within-group task-dependent activation was determined by SPM99 by using a threshold ($P < 0.001$, uncorrected) for defining the ROIs in the perisylvian language region, including both the Broca (Br) and Wernicke (Wn) areas and in the PMA. For each individual, the fMRI activation index (right) was then determined by integrating the BOLD signal changes in these ROIs for statistical comparisons. Two-sample *t*-tests were used to compare the mean of the activation index for each task. *, $P < 0.05$; **, $P < 0.01$; ns, no significance.

larger differences in the pattern of brain activation between the two groups speaking different languages when the task is less dependent upon language? Several key factors have been considered to contribute to those differences.

First, the brevity of number words in Chinese spoken language allows for faster processing and thus more of them to be represented depending upon short-term memory (Baddeley, 2000; Chein et al., 2002; Ravizza et al., 2004). This might explain the lower activation of perisylvian areas in the Chinese speakers ("I am not sure here what did you mean?"). There is another possibility that the *Comparison* condition with the largest arithmetic load requires most verbal short-term memory which might activate the anterior–posterior brain networks association with the perisylvian areas. This issue, however, should be addressed by further research using the tasks controlling for working memory.

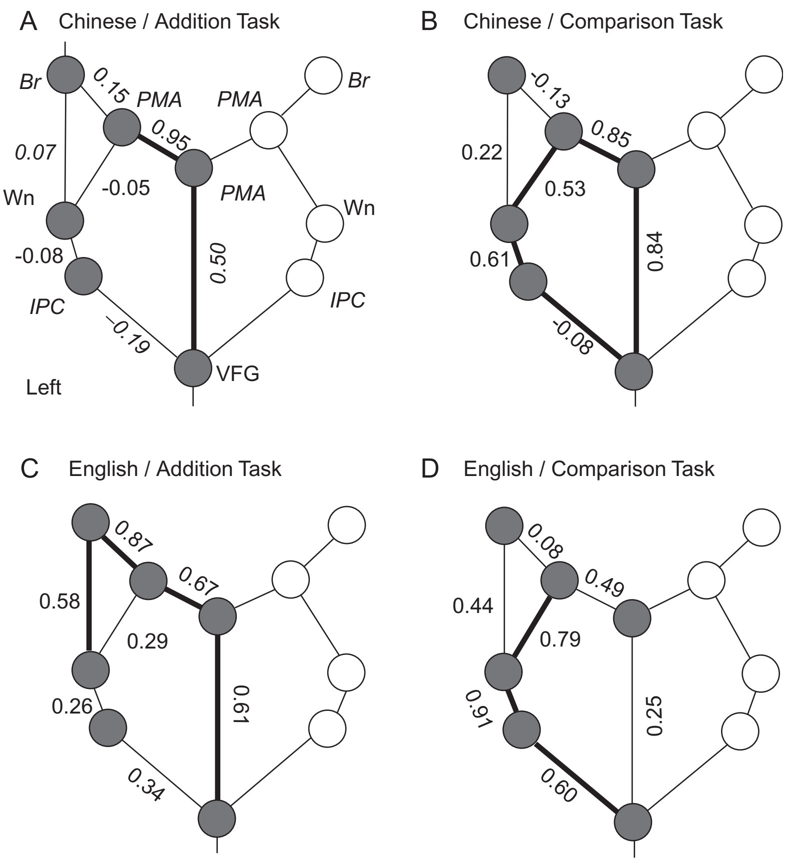

Fig. 3. Differential modulation of arithmetic processing in NCS and NES. The ROI-based functional connectivity analyses show the within-condition interregional covariance of the BOLD signal. (A) During the Addition condition in NCS. (B) During the Comparison condition in NCS. (C) During the Addition condition in NES. (D) During the Comparison condition in NES. The normalized cross-subject covariance ($-1<cc<1$) was calculated based on the individual BOLD signal changes in all of the ROIs defined in Figs. 1 and 2. A bold line between two regions (circles) indicates that the region-to-region correlation is statistically significant, reflecting the strength of an effective connection that is modulated by the task. In addition, the networks of the within-condition interregional covariance analysis constructed connections for each condition were statistically different ($P<0.05$) based on comparing one common connection [e.g., Br-Wn for *Addition*; SMA-visual fusiform gyrus (VFG) for *Comparison*] between NES and NCS. For showing the language dependence and for the simplicity, only the Broca area (Br), the PMA, the Wn, the intraparietal cortex (IPC) in the left hemisphere, and the bilateral SMA and VFG were included in the connectivity analysis.

Second, although the language-specific processing may contribute to those differences, the educational systems including learning environment, strategies, and cultural varieties may also have an influence on the acquisition and representation of numerical concepts, and these factors may result in differential brain processes (Posner and Rothbart, 2005; Campbell and Xue, 2001).

Educational systems

Educational systems are different in the East and West, especially in China and the United States (Leung et al., 2006). Campbell and Xue (2001) recruited Canadian university students either of Chinese origin (CC), or non-Asian origin Chinese (NAC) and Chinese university students educated in Asia to solve simple arithmetic problems in four basic operations (e.g., $3+4$, $7-3$, 3×4, $12\div3$) and reported their solution strategies. They also completed a standardized test of more complex multistep arithmetic. For complex arithmetic, Chinese students educated in Asia outperformed both CCs and NACs. For simple arithmetic, however, Chinese educated in Asia and CCs were equal and both performed better than NACs. The authors thought that the superior simple-arithmetic skills of CCs relative to NACs might derive from the extracurricular culture-specific factors rather than differences in formal education. NAC's relatively poor simple-arithmetic performance resulted from both less efficient retrieval skills and greater use of procedural strategies. Nonetheless, all the three groups reported using procedures for the larger simple subtraction and division problems, confirming the importance of procedural knowledge in skilled adults' performance of elementary mathematics. However, there are still other possibilities.

Because of using visual presentation in our previous study, reading experience may have shaped number processing. For example, the strong involvement of visuo-premotor association in the NCS may be related to the experience of reading Chinese logographic characters (Tan et al., 2003, 2006). A Chinese character is composed of strokes and subcharacters that are packed into a square configuration, producing a high, nonlinear visual complexity.

In elementary school, the students learn various strokes and space configurations and memorize the right location of a subunit (from left to right and top to down) for each character. This learning process is carried out by repeatedly copying samples of characters so as to establish the linkage among their orthographic, phonological, and semantic content. Tan et al. (2005) showed that the ability to read Chinese is strongly associated with a child's writing skills and extensive writing exercise during language acquisition. The very different reading experience in Western languages might contribute to the differences in number processing such as greater use of procedural strategies as Campbell and Xue (2001) showed in non-Asian origin Chinese's relatively poor simple-arithmetic performance. Campbell (2008) reported that educated adults often use addition reference to solve large simple subtraction problems, but that they may rely on direct memory retrieval for small subtractions.

Arithmetic strategies

Recent studies investigated the changes in functional neuroanatomy that occur as the Western individuals learn arithmetic problems (Delazer et al., 2003, 2005; Ischebeck et al., 2006). One study compared brain activation during the solving of trained and untrained arithmetic problems. Whereas trained problems showed greater activation of the left angular gyrus, associated with language, untrained problems were found to activate the intraparietal sulcus associated with the number line, suggesting a neural shift from the use of quantitative strategies to verbal retrieval as a function of arithmetic training (Delazer et al., 2003). Delazer et al. (2005) further investigated whether relative shifts in activation differ as a function of particular training methods. Specifically, "training by drill" (rote learning as the result of a two-operant problem) was compared with "training by strategy" (applying an instructed algorithm). Greater activation of the angular gyrus was found during the solving of problems learned by drill than during the solving of those trained using the strategy algorithm. Ischebeck et al. (2006) found that although the angular gyrus was activated more by trained than by untrained multiplication problems, the angular gyrus did not exhibit training effects for subtraction. Thus, the type of instruction and the particular arithmetic operation dynamically modulate the relative activation of intraparietal and left temporoparietal regions during arithmetic processing.

These results are consistent with the notion of ca core system of number, associated with the bilateral intraparietal cortex (IPC) and invariable across cultures, and a distinct perisylvian circuit associated with language- and education-specific strategies for storing and retrieving arithmetic facts (Dehaene and Cohen, 1995).

Genetic and early environmental factors

Representations of numbers occupy reproducible locations within large-scale macromaps, in the bilateral IPC. Dehaene and Cohen (2007) proposed a neuronal recycling hypothesis according to which cultural inventions invade evolutionarily older brain circuits and inherit many of their structural constraints. Since some early brain circuits involving numbers are common to all members of our species, they must be generally shaped by genes. However, genes do differ among individuals and groups. These polymorphisms or alleles are important not only in patients with disorders such as dyslexia and dyscalculia but also among normals. Thus individual differences in the efficiency of numerical networks are likely due in part to these genetic variations. Moreover, it is also known that the expression of genes can be influenced by environmental and training factors producing gene × environment interactions (Green et al., 2008). It is certainly possible that differences in pathways and efficiency in simple mental arithmetic may be due to different allelic patterns in Asian and Western groups. We propose gene–environment interaction framework including genetic factors, educational system, learning strategy, and experience that may contribute to the number processing, see Fig. 4.

Even if genetic variations can account for some of the differences that have been reported, it could still be the case that cultural differences can shape the brain process of number and arithmetic. The major domains of human cultural variability such as arithmetic are tightly constrained by our prior evolution and brain organization as "neuronal recycling hypothesis" proposed (Dehaene and Cohen, 2007). These are the areas where careful research would be needed to establish which genes, if any, are involved in group differences and discover how such genetic variation interacts with training and other cultural influences.

Future directions

Relationship between fronto-parietal networks

Studies suggest the involvement of fronto-parietal networks in the processing of symbolic and nonsymbolic magnitude in humans and nonhuman primates (Ansari et al., 2005; Menon et al., 2000; Nieder et al., 2002; Nieder and Miller, 2004). However, the functional connectivity between prefrontal and parietal activation is still unclear.

New analysis methods such as dynamic causal modeling and Grainger causality modeling of fMRI data may provide insight into network-based representations of numerical magnitude (Ansari, 2008; Friston et al., 2003; Roebroeck et al., 2005).

Interaction between number/arithmetic and language

Reading and arithmetic capacities are developing well into childhood and beyond. How do the differences in number words across languages come to influence the representation and processing of numerical magnitude in the brain? This question should be addressed in the future research.

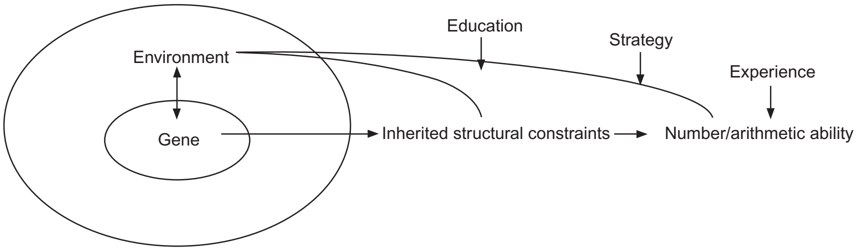

Fig. 4. Gene–environment interaction framework. We propose gene–environment interaction framework including genetic factors, educational system, learning strategy, and experience that may contribute to the number processing.

Gene and environment interaction

If additional evidence suggests that both gene and experience shape human cognitive functions such as number processing in the brain, the next challenge would be to understand how different education systems may change our core intuitions of number differently (Dehaene, 2009).

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