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Arithmetic processing in the brain shaped by cultures

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The universal use of Arabic numbers in mathematics raises a question whether these digits are processed the same way in people speaking various languages, such as Chinese and English, which reflect differences in Eastern and Western cultures. Using functional MRI, we demonstrated a differential cortical representation of numbers between native Chinese and English speakers. Contrasting to native English speakers, who largely employ a language process that relies on the left perisylvian cortices for mental calculation such as a simple addition task, native Chinese speakers, instead, engage a visuo-premotor association network for the same task. Whereas in both groups the inferior parietal cortex was activated by a task for numerical quantity comparison, functional MRI connectivity analyses revealed a functional distinction between Chinese and English groups among the brain networks involved in the task. Our results further indicate that the different biological encoding of numbers may be shaped by visual reading experience during language acquisition and other cultural factors such as mathematics learning strategies and education systems, which cannot be explained completely by the differences in languages *per se*.

Arabic numbers | fMRI connectivity | premotor association area

When presented with a simple math problem, $3 + 4 = \square$, two second-grade students, one speaking Chinese and the other English, would both have a quick and correct answer. By filling the blank with “7,” indicating an identical output along with the same visual input, this raises an interesting experimental question: are the underlying brain processes different between these two students? So far there has been little work directly addressing this issue, although previous studies implicated culture constraints on the brain processing of reading (1–3). The involvement of numbers in mental calculation has been associated with language processing as proposed by Dehaene and others (4–8). Despite different notations or verbal encodings conveying numerical meaning, it has been suggested that a brain network involving the intraparietal cortex (IPC) may provide semantic representation specific to quantity.

It is often difficult to compare the brain processes underlying such semantic representation crossing different languages without a common ground that allows direct comparisons. There is no language task common to both native Chinese and English speakers; for example, they respond to the stimulus “three” or “=” differently in orthography and phonology, although these different language characters have the same numerical meaning at a semantic level. However, Arabic digits, with the same visual input and meaning crossing different cultures, constitute a symbol system shared in mental calculation and linguistic representation. The usage of Arabic numbers in the present study also provides an opportunity to observe the language, especially the orthography-to-phonology or orthography-to-semantic mapping, and other differences between the two cultures. Therefore, this article clearly extends previous studies that have compared the Chinese and English languages, which, of course confound scripts with other differences.

In the current study using functional MRI (fMRI), we are able to directly compare the arithmetic task-induced changes in brain

activity between native English speakers (NES) and native Chinese speakers (NCS). Whereas previous neuroimaging studies have revealed differential activation patterns during reading processes (e.g., the temporal-parietal regions being activated in NES but the middle frontal gyrus in NCS), the question remains whether these differences are derived from culture characteristics rather than ethnic or hereditary factors (1, 9). We hypothesize that number representation and arithmetic processing in the brain may be affected by a variety of cultural factors such as educational systems and mathematics learning strategies that are beyond language-related experiences.

Results

The fMRI experiment was performed on a 1.5-tesla GE/SIGNA MRI scanner in Dalian Medical University, China. The NES group consisted of 12 foreign educators who were teaching English there, and the gender-, age-, and educational level-matched NCS group consisted of 12 local senior college students (see *Materials and Methods* for details).

Fig. 1 shows the brain activation patterns during two spatial orientation tasks (8): nonsemantic symbol notation (Symbol; Fig. 1*A Top*) and Arabic number notation (Number; Fig. 1*B Top*). In a sense, the Symbol condition could be used as a control because it has similar visual complexity with the Number condition. But we also used a specific control task as the baseline for removing the motor and nonspecific visual components of the tasks (see *Stimulation Materials*). It is unknown whether there are invariant brain activities across different cultures for the visual perception of physical symbols. Comparisons of the Symbol condition with the baseline may provide some insights. Meanwhile, the comparison of the Number condition alone with the baseline may simply illustrate different cortical representation of digits at a perceptual level between Chinese and English speakers.

Our fMRI results demonstrated that the Symbol task induced extensive changes of brain activity in the occipito-parietal cortices, inferior frontal lobe [Brodmann's areas (BA) 44 and 45], cerebellum, and sensorimotor areas (Fig. 1*A* and *C*). For both NES and NCS groups, the covert reading of nonsemantic symbols activated both the visuo-spatial pathway and, to some extent, the language pathway as well (10). Between-group comparisons during the Symbol condition yielded no significant differences in the fMRI signal (mapping data not shown). Although the left supplemental motor area (SMA) and inferior frontal lobe showed more extensive activation relative to NCS (a between-group subtraction did not reach a statistical significance level, see below), the overall brain activation during the representation of nonsemantic symbols was similar between these two

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Abbreviations: NES, native English speakers; NCS, native Chinese speakers; PMA, premotor association area; fMRI, functional MRI; IPC, intraparietal cortex; SMA, supplemental motor area; BA, Brodmann's area; ROI, region of interest; BOLD, blood oxygen level-dependent; Wn, Wernicke area.

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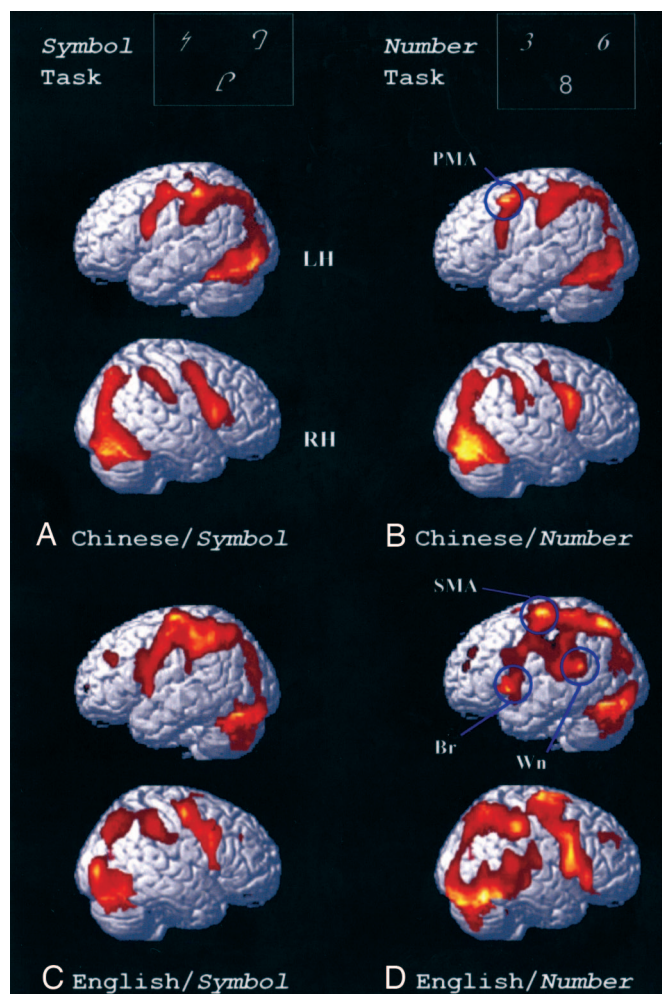


Fig. 1. Dissociation in the brain representation of Arabic numbers between NCS and NES (see *Materials and Methods*). (A) During the Symbol task in NCS. (B) During the Number task in NCS. (C) During the Symbol task in NES. (D) During the Number task in NES. The task-dependent brain activation was determined by SPM99 (32) 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 (automated anatomical labeling) (www.fil.ion.ucl.ac.uk/spm/ext/#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 task and Number task, respectively, are shown at the top. LH, left hemisphere; RH, right hemisphere; Br, Broca area.

groups, implicating a highly preserved symbol representation system in both populations.

Remarkable differences between NES and NCS were found during the condition of Number representation, especially in the left hemisphere (Fig. 1 *B* and *D*). The activation in NES is greater in the left SMA, Broca area, and Wernicke area (Wn), compared with the corresponding areas in NCS. Meanwhile, the occipito-parietal pathway, sensorimotor areas (including the cerebellum), as well as the frontal cortex, show a similar level of activation for both NCS and NES during the Number condition, which is congruent with the suggestion that the classical number-processing model involves verbal, analogue, and visual components (4, 5). Importantly, much larger brain activation was found at a region in-between BA6, BA8, and BA9 in NCS. We termed this region as a premotor association area (PMA), which has been previously associated with visuo-spatial processing and

various functions more closely related to cognitive than to motor processes in humans and nonhuman primates as well (11–18).

Interestingly, within-group comparisons also reveal a similar activation pattern between Symbol and Number conditions in NCS (Fig. 1 *A* and *B*). This result was further supported by the direct contrasts of the differences in Number minus Symbol subtraction, which did not reach a statistically significant level for the NCS group (mapping data not shown). Such similarity between these two conditions, plus the PMA activation, may imply the utilization of a visual-symbol system for representing Arabic digits in Chinese speakers. On the other hand, in NES, apparent differences were found between Symbol and Number conditions (Fig. 1 *C* and *D*). We also performed direct comparisons by Number minus Symbol subtraction in the NES group (mapping data not shown), in which the classical language network including the left SMA, Broca area, and Wn showed much larger activation during the Number condition. Such different activation patterns may further indicate dissociation in the notation of numerical quantities at a neurobiological level.

Quantitative analyses in two regions of interest (ROI) and direct contrasts in the fMRI signal between the NES and NCS groups demonstrated clearly more differences in the brain processing of numbers (Fig. 2). Such differences were even more pronounced during two simple arithmetic tasks (8): a simple addition task (Addition) and a quantity comparison task (Comparison) (see *Materials and Methods*). These two tasks were formulated on the basis of the Symbol and Number tasks to contrast the mathematical loading as it becomes larger and larger cross all these four conditions: Symbol < Number < Addition < Comparison.

Consistent with results in Fig. 1, there were no significant between-group difference for the Symbol condition at both the perisylvian area (including Broca and Wernicke) and PMA area (see bar graphs in NES and NCS in Fig. 2). For the other three conditions, although the similar activated networks were found in the occipito-parietal areas, perisylvian area, and PMA area, the perisylvian activations are significantly larger in NES than those in NCS (Fig. 2*A*). It should be noted that we have not found between-group differences in the occipito-parietal regions for all of the four conditions (data not shown). These results are consistent with previous suggestions (8, 19) that (i) simple addition is mediated by automatic retrieval and a verbal process relying on the perisylvian language cortices and (ii) the proximity comparison between numerical quantities engages the parietal cortex (5, 6).

The larger perisylvian activation in NES alone may suggest that the brain representation of numbers is influenced by different language processes. However, across all of the four conditions as the arithmetic loading increased, there was a trend of increase in the premotor activation in NCS but not in NES (bar graph; Fig. 2*B*). Such a trend was also found at the perisylvian area in NES but not in NCS (Fig. 2*A*). Therefore, between NCS and NES, there was a double dissociation in the brain activation during these tasks, which suggests that the differences may not be merely due to different languages but also due to specific mathematic processes. In other words, whereas the numbers are represented in different brain regions from those involved in languages, people speaking Chinese or English may engage different neural pathways in numerical processing.

To further demonstrate such dissociation, we used an fMRI connectivity analysis method (20–23), which yielded distinct functional pathways corresponding to different tasks, respectively (Fig. 3). We argue that the interpretation of imaging data should not solely rely on the analysis of segregated regions. Although the performance of a task shares common brain structures that may have intrinsic fiber connections, these connections may not be actively expressed in the functioning network during the task. For example, all of the ROIs defined in the above activation maps (Fig. 1) could be used for connectivity

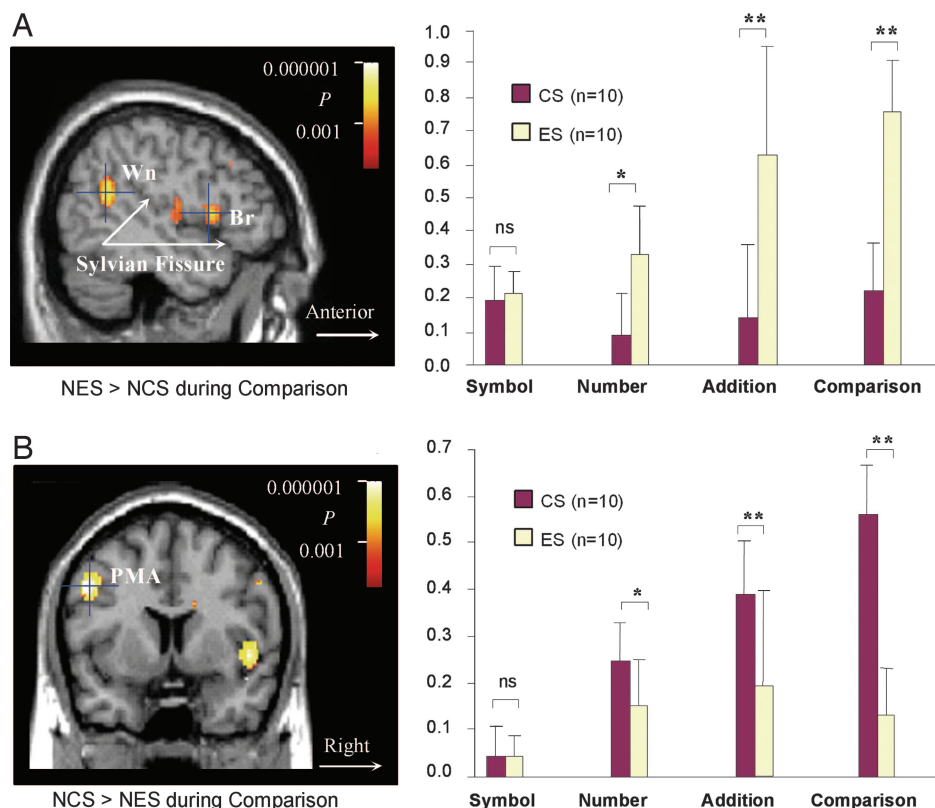


Fig. 2. Comparison of the activation intensity between NCS and NES in the perisylvian language region (A) and the PMA (B). The brain activation maps (Left) were determined by contrasting BOLD signal between NCS and NES only during the Comparison task, with the NES group showing relative increase of the 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 area (Br) with Talairach coordinates at $(-50, 12, 7)$ and Wn $(-57, -59, 16)$, and in the PMA $(-18, 22, 56)$. 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 ($n = 10$).

analysis based on the significant within-condition interregional covariance (21, 22) (see *Materials and Methods*), but a functional network specific to arithmetic processing may spare some of these ROIs. For simplicity, we only selected the ROIs in the left hemisphere in a network for the connectivity analysis, and this network was constructed based on a network of the brain areas that were activated by Symbol task and/or Number task (Fig. 1).

Our results show that during the simple Addition task, which involves minimal arithmetic operation, there is a strong interaction between the visual cortex and premotor motor areas. The visual activation may implicate a process of “online searching” or automatically retrieving math fact, which also involves dlPFC activation for working memory (data not shown). Math fact retrieval involves visual processing, and working memory has been demonstrated by others (6, 8). We speculate that, because the functional network spares the IPC, the involvement of the visuo-premotor pathway under the Addition condition is not specific to arithmetic processing *per se* in both NCS and NES (11, 13, 16). Whereas there is a visuo-premotor interaction (including the SMA) common to both NCS and NES (Figs. 3A and C), NCS shows relatively stronger premotor association ($CC_{SMA-PMA} = 0.95$ in Fig. 3A) compared with NES ($CC_{SMA-PMA} = 0.67$ in Fig. 3C). In NES, the visuo-premotor pathway was extended to the Broca area, implicating strong verbal dependence of the math fact retrieval that may be mediated by phonological processing (4, 5). In NCS, however, the retrieval processing showed a much weaker activation in the Broca area, suggesting that the area for verbal processing was not engaged. These results reveal the

difference in language processing for the simple Addition task between NCS and NES.

More distinct patterns were shown in the functional networks specific to the Comparison condition for the two groups (Fig. 3B and D), manifesting a dorsal visuo-pathway dominance (through the parietal-occipital cortex) in NCS but a ventral visuo-pathway dominance (through the temporal cortex) in NES for mental calculation. Contrasting to Addition, Comparison strongly involves a high level of Wn-IPC correlation in both NCS and NES, which is consistent with the suggestions that the Wn and IPC are involved in the encoding of analogue quantities (4–8). Given no significant difference in this connection, it is explicable that the computation outcome would hold the same meaning to both Chinese speakers and English speakers. However, mental operation for transcoding the visual numerical codes to its semantic output codes may be different between NCS and NES. Shown in our results, there were strong connections between the visual cortex and supplementary motor area in NCS but not in NES for Comparison. Mediated by the PMA, this visuo-pathway extends to the Wn-IPC pathway, implicating a visuo-premotor association neural network specific to mental calculation in NCS. In NES, the connection between the visual cortex and supplementary motor area seems not functionally expressed under the Comparison condition, but there is a strong correlation between the visual cortex and intraparietal cortex, implicating a functioning ventral pathway. Note that Comparison spares the Broca area in the functional network for both NCS and NES (Fig. 3B and D), further suggesting that the difference may not be due to the factors in phonological encoding.

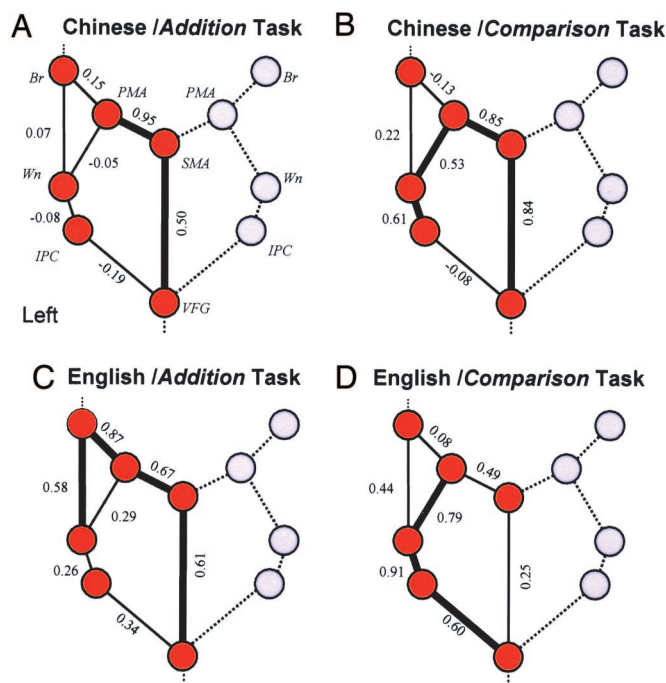


Fig. 3. Differential modulation of arithmetic processing in NCS and NES. The ROI-based functional connectivity analyses show the within-condition interregional covariance of the BOLD signal (see *Materials and Methods*). (A) During the Addition condition in NCS. (B) During the Comparison condition in 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.

Discussion

Our findings have two implications. First, in both Chinese and English speakers, there is cortical dissociation between addition and comparison processing. The arithmetic 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 (4, 5). Second, there are differences in the brain representation of number processing between Chinese and English speakers. These two different language systems can shape the way to process non-language-related content. In other words, number processing differs in those with Chinese and English backgrounds. Shown by weak perisylvian activation and no Broca association in NCS (but not NES), language would be expected to matter more in the arithmetic than in the comparison task. If so, why during comparison are there much larger differences in the pattern of brain activation between NES and NCS when the task is less dependent upon language? It is noted that the brevity of the Chinese language for numbers allows for a larger short-term memory (24), and such faster processing in the language system might explain the lower activation of perisylvian areas in NCS. Although language-specific processing may contribute to those differences, the learning environment and cultural varieties may also have an influence on the acquisition and represen-

tation of numerical concepts, and these factors may result in differential brain processes (25–27).

More specifically, because of using visual presentation in the present study, reading experience may have shaped number processing. For example, the strong involvement of visuo-premotor association in NCS may be related to the experience of reading Chinese characters (15, 28). A Chinese character is composed of strokes and subcharacters that are packed into a square configuration, possessing 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 through repeatedly copying samples of characters so as to establish the linkage among orthographic, phonological, and semantic content of Chinese characters. Tan *et al.* (15) showed that the ability to read Chinese is strongly associated with a child's writing skills and extensive writing exercise during language acquisition. The use of the abacus in many Asian schools also suggests that, in one way or the other, the engagement of a "mental image" for arithmetic could be related to the differences in brain activation (29). Arabic digits are frequently used as date, time, and series order mixing with Chinese as well as English characters in printed scripts. It has been suggested that the mixed usage of different symbols shaped neural development and organization (30). Upon completion of elementary school education, Arabic numbers have been learned and the acquisition of numerical knowledge and simple calculation skill are completed. Those well formulated learning processes, which are beyond reading system and known to be both educationally and socially different, may lead to brain differences during number processing and other cognitive tasks (31).

Materials and Methods

Subjects and Tasks. Twelve native Chinese speakers [NCS group, 6 male/6 female; mean age (\pm SD) = 23.8 ± 0.8 yrs; educational level, college] and 12 native English speakers [NES group, 6 male/6 female; mean age (\pm SD) = 26.8 ± 2.3 yr; educational level, college] participated. The Chinese participants in the NCS group are senior students from the local universities in Dalian, China. The participants in the NES group all are educators teaching English language in the city of Dalian; eight of them are from the United States of America, two from England, one from Canada, and one from Australia, and none of them are Asian or Chinese Americans. All subjects are right handed and physically healthy. The human experiment was approved by a local Institutional Review Board, and informed consent was obtained from each participant. Two subjects from the NCS group and two from the NES group were excluded from results because of their head motion during the experiment; the remaining subjects in both groups had the same gender ratio.

Four conditions were investigated, and the design of behavioral tasks was adapted from a previous study with slight modification (8, 10): (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 character had the same orientation as the first two. Taking Fig. 1*A Top* as an example, the third symbol (in the second line) has the same orientation with the two symbols in the first line, and subjects need to press the "YES" button. (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). Taking Fig. 1*B Top* as an example, the third digit "8" (upright) has a different orientation with the two digits "3" and "6" (italic), and subjects need to press the "NO" button. (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. A baseline condition was used to control the motor and nonspecific visual components of the tasks (for actual visual stimuli and detailed task design, see *Stimulation Materials*).

The experiment consisted of four separate scanning sessions. Each session had three task blocks, which were alternated with three blocks of a control baseline. Each block lasted for 20 s in which a series of triplets of visual stimuli were presented by back-projection onto a translucent screen. A triplet was presented with a pair of stimuli appearing first on the screen and the third stimulus appearing 500 ms after. The subject responded according to the task instruction with a button pressing, which made the triplet disappear and initiated the next trial. The reaction time (RT) and accuracy of task performance were recorded by using E-PRIME (Psychology Software Tools, Pittsburgh, PA). No significant differences in both the RT and accuracy were found between the NCS and NES groups.

MRI Techniques. MRI scans were performed at the First Affiliated Hospital of Dalian Medical University by using a 1.5-tesla MRI scanner (GE/SIGNA, Milwaukee, WI). A T2*-weighted gradient-echo echo planar imaging (EPI) sequence was used for fMRI scans, with the matrix size 64×64 , field of view (FOV) $240 \text{ mm} \times 240 \text{ mm}$, slice thickness 7 mm (1 mm inter-slice gap), and repetition time/echo time/flip angle = 2,000 ms/40 ms/90°. Sixteen axial slices parallel to the anterior commissure–posterior commissure line were acquired to cover the whole brain. High-resolution anatomical images were collected by using a T1-weighted, three-dimensional gradient-echo sequence for registration of functional images and localization of brain activation.

Data Analysis. SPM99 was used for image preprocessing and voxel-based statistical analyses (www.fil.ion.ucl.ac.uk/spm). Images were first spatially realigned, normalized, and smoothed (8-mm full width at half-maximum). Statistical analysis used a random effect model, with individual activation maps being generated using the general linear model (32). The voxel-wise threshold for activation was set at $P < 0.05$, corrected for the number of resolution elements in each of the ROIs by using the SPM small volume correction (SVC) procedure together with brain masks defined by the automated anatomical labeling toolbox (www.fil.ion.ucl.ac.uk/spm/ext/#AAL). The brain masks defined the brain regions over each of which the SVC was performed. These brain regions included fusiform, inferior frontal gyrus, SMA, inferior parietal cortex, precentral gyrus, and superior temporal gyrus, which were used for further functional connectivity analyses. Differences in the task-induced activation between the two groups were examined with two-sample t tests, and statistical threshold was set at $P < 0.001$ uncorrected (32). The functional brain regions were reported in the Talairach space, after adjustments for differences between Montreal Neurological Institute (MNI) and Talairach coordinates (www.mrc-cbu.cam.ac.uk/Imaging/Common/mnispaces.shtml).

We applied the within-condition interregional covariance analysis (WICA) method for ROI-based functional connectivity analyses (21, 22). For each task, functional modulation of brain circuitry was modeled through cross-correlation analysis of blood oxygen level-dependent (BOLD) signal over three task blocks and over 10 subjects in each group. For simplicity, in the

current study, we limited our analysis in the preselected ROIs or a network of areas that were activated during the Symbol condition and/or Number condition (Fig. 1). These areas included the PMA, the Broca area, the Wn, and the IPC in the left hemisphere, and the bilateral SMA and visual fusiform gyrus (VFG). The averaged BOLD signal for each task block was individually calculated for each ROI in a network defined both anatomically and functionally on the activation maps. The between-ROI correlation was then calculated for the Addition and Comparison conditions (Fig. 3), and the significance level ($P < 0.05$) of the correlation between activation magnitudes was assessed separately by using one-tailed t tests (21, 22) and jointly correcting the number of hypothesized connections for within each subject group and under each of the two conditions (Additions and Comparisons). In addition, the WICA-constructed connection differences in covariance were compared between NES and NCS.

Stimulation Materials. In the Symbol task, nine nonsemantic characters or symbols were created so as to avoid any lexicalization (no alphanumeric characters, no conventional printed symbols) and to match their visual complexity with that of Arabic digits (8). The triplets used in each task consist of three such nonsemantic characters or three Arabic digits from 1 to 9 displayed in white color on a black background. In all conditions, half of the pairs are in an italic orientation and the remaining half in an upright orientation; the third stimulus in a triplet has equally either italic or upright orientation in a task block. In all of the three numerical conditions, the pairs are identical but appear in a random order in each block, and the third digit is selected with several constraints according to Pesenti *et al.* (8). In a typical sequence of events for the Symbol task, subjects were instructed to decide by pressing a button whether or not the third character has the same orientation as the first two. For the Number task, subjects were instructed to decide whether or not the third digit had the same orientation as the first two. For the Addition task, subjects were instructed to decide whether or not the third digit was equal to the sum of the first two. For the Comparison task, subjects were instructed to decide whether or not the third digit was larger than the larger of the first two. For the Control task, white and/or gray circular dots were used as visual stimuli in the triplets presented in a random order. The sequence of events for the Control task was the same as that in the Symbol task. The task was to decide whether or not the third dot in a triplet had the same color as the pair of dots presented first. In a previous study, a resting state with eyes closed was used as control baseline. However, recent studies showed that even the resting brain was imposed by a default model of activation (33). As a result, the task-induced brain activation may be confounded with the activity during the resting state. The current design may avoid such a confounding situation and control for the motor and nonspecific visual components in the other four tasks.

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