Neural correlates of numbers and mathematical terms

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ABSTRACT

Numerical processing has been demonstrated to be subserved typically by the brain regions around the bilateral intraparietal sulcus (IPS). The goal of the current study was to investigate whether the processing of mathematical terms shared the same brain regions with numerical processing. Healthy adult participants performed semantic distance judgment tasks on five types of materials, including geometric terms, algebraic terms, linguistic terms, words for tools and other common objects, and Arabic numbers. Brain activation was measured with functional magnetic resonance imaging (fMRI). The results showed that geometric terms had greater activation than algebraic terms, linguistic terms and tool words in the horizontal IPS, but algebraic terms did not have greater activation than linguistic terms and tool words in this region. Arabic numbers showed greater activation than non-number materials (including geometric terms, algebraic terms, linguistic terms and tool words) in the bilateral IPS, right inferior frontal gyrus and bilateral middle frontal gyrus, but the non-number materials showed stronger activation in the left inferior frontal gyrus and left middle temporal gyrus. These results suggest that the brain area for the processing of numbers (the left IPS) seems to be involved in semantic processing of geometric terms, but not that of other mathematical terms such as algebraic terms. Both algebraic and geometric terms share similar brain organization with basic semantic processing in the left temporal and frontal regions.

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Introduction

Several lines of research have shown that numerical processing is subserved by the bilateral intraparietal sulcus (IPS) (e.g., Arsalidou and Taylor, 2011; Butterworth, 1999; Dehaene et al., 1999; Eger et al., 2003; Kadosh et al., 2005, 2007; Piazza et al., 2007; Thioux et al., 2011; Butterworth, 1999; Dehaene et al., 1999; Eger et al., 2003; Kadosh et al., 2005, 2007; Piazza et al., 2007; Thioux et al., 2005; see reviews by Brannon, 2006; Dehaene et al., 2003). First, patients with parietal lesions consistently show selective impairments in numerical skills (e.g., Dehaene and Cohen, 1997; Denes and Signorini, 2001; Grafman et al., 1982; Takayama et al., 1994; Warrington, 1982; Zorzi et al., 2002), whereas patients with lesions to other brain regions showed preservation of numerical skills (e.g., Butterworth et al., 2001; Cappelletti et al., 2001, 2002, 2005; Crutch and Warrington, 2002; Diesfeldt, 1993; Jefferies et al., 2004, 2005; Lemor et al., 2003; Zamarian et al., 2006). Second, functional MRI studies have systematically shown that numerical processing elicits greater activation in the parietal lobe than does non-numerical processing (e.g., Ansari et al., 2006; Cappelletti et al., 2010; Eger et al., 2003; Knops et al., 2006; Le Clec‘H et al., 2000; Piazza et al., 2004; Thioux et al., 2005; Zago et al., 2008; but see Göbel et al., 2004; Kadosh et al., 2008; Shuman and Kanwisher, 2004). Third, developmental dyscalculia has also been shown to be associated with structural abnormalities in the IPS regions (e.g., Isaca et al., 2001; Kucian et al., 2006; Molko et al., 2003, 2004; Rotzer et al., 2008).

Based on the neuropsychological and neuroimaging evidence, Dehaene et al. (2003) proposed a three parietal circuit model for numerical processing: That is, the bilateral intraparietal system is associated with quantity representation, the left angular gyrus serves the purpose of general information processing, such as the working memory (Arsalidou and Taylor, 2011). Although the evidence is clear that numbers are specifically processed by the IPS, less is known about the neural substrates for the processing of knowledge about mathematical terms (e.g. “decimal”, “fraction”, “group”, “rectangle”). On the one hand, mathematical terms are verbal materials that are supposed to be processed in the...
language network. On the other hand, they are related to numbers and other aspects of mathematics (e.g., spatial relations in geometry) that are processed by the IPS. To our knowledge, only three neuropsychological studies (Delazer and Benke, 1997; Hittmair-Delazer et al., 1994; Warrington, 1982) and three neuroimaging studies (Andres et al., 2011; Prado et al., 2011; Zhou et al., 2007) have shown limited but relevant results. Warrington (1982) found that lesions in the left parietal cortex led to a loss of memory of arithmetic facts but had no effects on the conceptual knowledge of arithmetic (e.g., operations, commutativity, addition/subtraction inverse principle). These results were confirmed by Hittmair-Delazer et al. (1994). In contrast, Delazer and Benke (1997) found that a patient who suffered from a left parietal glioblastoma completely lost conceptual knowledge of arithmetic, but preserved some arithmetic facts (multiplications, some additions and subtractions). Using fMRI, Zhou et al. (2007) found that addition had more activation in the right superior and inferior parietal lobules than multiplication, whereas the latter had more activation in some of the language-related regions such as the left posterior and anterior superior temporal gyrus. Prado et al. (2011) found a similar disassociation between the analogical and language-based representations of numbers. Andres et al. (2011) used transcranial magnetic stimulation (TMS) to demonstrate that multiplication had greater activation in the bilateral middle and superior temporal gyri than subtraction, though both relied on the horizontal IPS.

These results suggest that the memory of conceptual knowledge of arithmetic may be subserved by the left parietal cortex or the language-related regions such as the left frontal cortex and left temporal cortex. The current fMRI study aimed to examine systematically the processing of two types of mathematical terms—geometric (e.g., “sphere”, “trapezoid”) and algebraic terms (e.g. “even number”, “fraction”). The processing of mathematical terms was compared with that of three types of materials: Arabic numbers, linguistic terms (e.g. “noun”, “poem”), and tool words. The tool words actually included both words for tools (e.g. “scissors”, “rake”) and those for other common objects (e.g. “piano”, “candle”), following the convention of previous studies (e.g., Cappa et al., 1998; Martin et al., 1996). The present study used the semantic distance judgment task (Mummery et al., 1998; Zannino et al., 2006). If mathematical terms involve only verbal processing, we would expect the activation patterns of geometric and algebraic terms to be similar to those of the two types of verbal materials (linguistic terms and tool words). On the other hand, we expected that algebraic terms would activate mental representations of numbers. For example, “odd number” would activate the numbers “1, 3, 5, 7, 9,...”, “fraction” would activate the numbers “1/2, 1/3, 1/4,...”, and “negative number” would activate the numbers “−1, −2, −3, ...”. Therefore, we expected greater activation in the IPS for the algebraic terms than for linguistic terms and tool words. Similarly, we expected that geometric terms such as “radius”, “arch”, “trapezoid”, and “vertex angle” would activate mental images of the actual geometric shapes, and hence elicit greater activation in the inferior parietal lobe, which has been found to be involved in processing mental images (e.g. Alivisatos and Petrides, 1997; Carpenter et al., 1999; Gauthier et al., 2002; Jordan et al., 2001; Vingerhoets et al., 2001).

Methods

Subjects

Twenty right-handed (10 male; aged 18.8–22.5 years old, and mean age = 20.6 years old) undergraduates were recruited from Beijing Normal University. These subjects reported having no previous history of neurological disorders or head injury. Procedures of the experiment were fully explained to all subjects before they gave informed consent. This study was approved by the Institutional Review Board (IRB) of the Institute of Cognitive Neuroscience and Learning at Beijing Normal University.

Stimuli and materials

Stimulus presentation and recording of behavioral data were programmed using Microsoft Visual Basic 6.0 (Chinese Version) on a Pentium 4 laptop. Stimuli were projected onto a translucent screen placed at the back of the magnet bore. Participants viewed the screen through a mirror mounted on the head coil, at a distance of ~30 cm from the eyes.

Five types of materials were used: algebraic terms, geometric terms, linguistic terms, tool words, and Arabic numbers. They were presented in black against a light gray background (the RGB value was 200, 200, 200). The height of the stimuli was set to ~10°. The width of the Chinese characters and that of the numbers were matched (mean visual angle was ~15°).

Subjects were asked to perform the semantic distance judgment task (Mummery et al., 1998; Zannino et al., 2006) (see below for the specific procedure). For each type of materials, we used 58 terms or numbers (see Appendix A). Subjects were pre-tested to ensure that they knew the exact meaning of every term. For mathematical terms that have alternative meanings (e.g., “he” means “sum” and “harmony” among others), subjects were told that in this study they should focus on the mathematical meanings in order to perform the semantic judgment task.

Procedure

Before scanning, subjects received a training session to ensure that they understood the instruction of this experiment. The scanning session lasted about half an hour and was organized into three runs, each consisting of five experimental blocks (one 9-trial block for each condition or type of material) and five fixation blocks (with “+” at the center of the screen). The balanced Latin square design (Bradley, 1958) was used to counterbalance the order effect of the 5 types of materials. The five material types (being coded as “1”, “2”, “3”, “4”, “5”, respectively) can be permuted into 10 types of sequences, including 12534, 23145, 34251, 45312, and 51423, and their reversed sequences. The 10 sequences were repeated 6 times to create a total of 60 sequences, which allowed each subject of the 20 subjects to have 3 different sequences.

Each run in the experiment lasted 5 min. Each experimental block lasted for 36 s, and the fixation block for 24 s (see the experimental procedure in Fig. 1). There was a 1–2 min rest after each run.

Subjects were presented triplets of stimuli (one on the top and two at the bottom, see Fig. 1). Their task was to decide which of the two terms or numbers at the bottom were semantically more similar to the term or number above. They responded by pressing either the key on the left response box using the left index finger or the key on the right response box using the right index finger. Both accuracy and speed were emphasized.

fMRI data acquisition

Imaging was performed on a Siemens (Munich, Germany) 3T Trio scanner using a standard eight-channel head coil. After automatic shimming of the magnetic field, three-dimensional (3D) high-resolution T1 anatomical images were acquired for coregistration with the functional images. Next, functional volumes were acquired using a multiple slice T2-weighted echo planar imaging (EPI) sequence with the following parameters: repetition time = 2000 ms; echo time = 30 ms; flip angle = 90°; matrix dimensions = 64 x 64; field of view = 200 mm; and slice thickness = 4 mm. Thirty-two slices covered the entire brain.

Statistical analysis of the fMRI data

Individual MRI data sets were analyzed using the SPM5 software (Wellcome Department of Imaging Neurosciences, University College
London, UK, http://www.fil.ion.ucl.ac.uk/spm). All volumes were realigned to the first volume and spatially normalized to a common value in order to correct for whole brain differences over time. Images were then smoothed using an isotropic Gaussian kernel of 4 mm and high-pass filtered at a cut-off of 128 s.

We first calculated parameter-estimated images for individual subjects across the whole brain. Then we conducted group analyses with random effects by applying the one-way ANOVA (analysis of variance) in SPM5 on the brain activation maps of all subjects, with material type as the independent variable. We first calculated the brain activation for each type of material relative to fixation. The contrasts among the brain activation for the five types of materials were then conducted. The conjunction analysis on selected contrasts was also conducted. A moderate threshold $p<.001$ (uncorrected) was used in the above analyses except for the contrast analysis among conditions. We used a lenient threshold $p=.008$ (uncorrected) for contrast analysis in order to detect weak differences among conditions.

To examine the role of the parietal cortex, especially the IPS, in the processing of mathematical terms, we then conducted ROI (region of interest) analysis. Two types of independent localizers were used. First, we defined ROIs based on the parietal regions in the widely-cited Dehaene’s three parietal circuit model for number processing (Dehaene et al., 2003). The regions include bilateral horizontal segment of the intraparietal sulcus (IPS) for numerical quantity processing, and the bilateral posterior superior parietal lobule (PSPL) for spatial attention in numerical processing. We defined five ROIs, each as a sphere with a radius of 6 mm, centered on the coordinates for each brain region specified in Dehaene et al.’s model. Second, we defined ROIs based on the differences in brain activation between two types of materials used in the current study: Arabic numbers and tool words. According to a previous study (Thioux et al., 2005), numbers would have greater activation in the parietal cortex and prefrontal cortex. The functional ROIs were defined by the differential activation in the “numbers–tool words” contrast for the following six brain regions: the left inferior parietal lobule (IPL), left superior parietal lobule (SPL), left middle frontal gyrus (MFG), right IPL, right SPL and right MFG. These ROIs were used to compare the brain activation elicited by three types of terms: geometric, algebraic and linguistic terms.

The positive beta values in the ROIs in the con_*_img files were extracted with our in-house software for brain image data processing written in MATLAB 7.1 (Math Works Inc., Natick, MA, USA). The repeated measures ANOVA on the beta values was performed to detect the effect of type of materials. The MRcron software (http://www.sph.sc.edu/comd/rorden/mricron/, Rorden et al., 2007) was used to visualize the brain activation.

Brain laterality in the processing of numbers and mathematical terms

To examine hemispheric asymmetries in the processing of numbers and mathematical terms, we selected four Brodmann areas (BA) in the parietal and prefrontal regions according to the study byArsalidou and Taylor (2011): that is, BA 7 and BA 40 in left and right parietal cortex; BA 9 and BA 46 in left and right middle frontal gyrus. The BAs were created by using the anatomically defined template in WFU PickAtlas toolbox (http://www.anir.wfubmc.edu, Maldjian et al., 2003). Laterality index was calculated as: $LI = (N_L - N_R)/(N_L + N_R)$, where $N_L$ and $N_R$ were defined as the number of voxels above the intensity threshold $p<.001$ (uncorrected) in the left and right BAs (Seghier, 2008). The laterality index was deemed left dominant when $LI > 20$, and right dominant when $LI < -20$, and values in-between were considered bilateral (Deblaere et al., 2004; Springer et al., 1999).

Results

Behavioral results

The mean reaction times (RTs) were 1856 ms for Arabic numbers, 1901 ms for geometric terms, 1867 ms for algebraic terms, 1855 ms for linguistic terms and 1866 ms for tool words. The mean error rates were 14.80%, 9.95%, 11.30%, 10.30%, and 10.90%, respectively. RTs and accuracy rates were analyzed with a repeated measures analysis of variance (ANOVA) (five types of materials: algebraic terms, geometric terms, linguistic terms, tool words and Arabic numbers). The main effect of stimulus type was not significant for either RTs, $F(1,19) = 185, p = .95$, or the error rates, $F(1,19) = 1.84, p = .19$.

Whole-brain analysis

The brain activation data for each type of material relative to fixation, including coordinates, activation volumes, maximum intensities and so on, are displayed in Table S1 in Supplementary Online Materials. The conjunction of the brain activation across the five types of materials is shown in Figure S1 in Supplementary Online Materials. Results showed that the five types of materials were commonly processed in the left inferior and superior parietal lobule, left inferior frontal gyrus, bilateral supplementary motor area, right angular, and left putamen (Table 1).

Details of the differences in brain activation from the direct contrasts are displayed in Table S2 in the Supplementary Online Materials. Arabic numbers elicited greater activation than the word materials (i.e., geometric terms, algebraic terms, linguistic terms and tool words) at the bilateral IPS, bilateral middle frontal gyrus.
and right inferior frontal gyrus, but the word materials had greater activation typically at the left inferior frontal gyrus and left middle temporal gyrus (See Table 2 and Fig. 2). Geometric terms showed greater activation than the non-mathematical word materials (i.e., linguistic terms and tool words) at the left IPS and the left inferior temporal gyrus (See Table 3 and Fig. 3).

ROI analysis

Based on the ROIs in Dehaene's three parietal circuit model (Dehaene et al., 2003), we found that four ROIs except the left angular gyrus (AG) showed significant differences across the five types of materials: the right IPS, F (4, 76) = 24.90, p < .001; the left IPS, F (4, 76) = 7.22, p < .001; the right PSPL, F (4, 76) = 18.70, p < .001; the left PSPL, and F (4, 76) = 5.92, p < .001 (Fig. 4). Further multiple comparison tests of activation in these regions showed that Arabic numbers elicited significantly greater activation than other four conditions. Geometric terms showed greater activation in the left IPS than did algebraic terms, linguistic terms, and tool words. Geometric terms also showed greater activation in the left PSPL than did algebraic terms and tool words, but geometric terms only showed greater activation in the right IPS than did algebraic terms.

Using the functional ROIs defined by “Arabic numbers–tool words”, we found marginally significant differences among geometric, algebraic, and linguistic terms in the left IPL ROI (MNI coordinates, XYZ: −48 −39 39), F (2, 38) = 2.53, .05 < p < .10, in the right IPL ROI (X: 48–45 51), F (2, 38) = 3.00, .05 < p < .10. Further multiple comparison tests of activation in the left IPL ROI showed that geometric terms had greater activation than algebraic terms and linguistic terms, and geometric terms also showed greater activation in the right IPL ROI than did algebraic terms. These results are consistent with ROI analysis presented above based on Dehaene’s three parietal circuit model.

No significant effects were found in other ROIs, including the left SPL ROI (X: −21 −57 54), right SPL ROI (X: 18–78 54), left MFG ROI (X: −27 33 36) and right MFG ROI (X: 42 36 24). The brain activation results are displayed in Fig. 5.

Brain laterality of processing of numbers and mathematical terms

Laterality indices are presented in Fig. 6. Arabic numbers showed bilaterality in the parietal cortex (BA 7 and BA 40), but right laterality in the prefrontal cortex (BA 46). All three types of mathematical terms and tool words consistently showed left laterality in the parietal cortex and prefrontal cortex (BA 7, BA 40, BA 9, and BA 46).

Discussion

The goal of the current study was to investigate the neural correlates of the processing of two types of mathematical terms (geometric and algebraic terms). Control materials were Arabic numbers, linguistic terms, and tool words. The main findings include: (1) Algebraic terms did not elicit greater activation than did linguistic terms and tool words in the horizontal intraparietal sulcus, but geometric terms elicited greater activation than did algebraic terms, linguistic terms and tool words in this brain region; (2) Arabic numbers had significantly greater activation than other four types of materials in the bilateral IPS, the right inferior frontal gyrus, bilateral middle frontal gyrus and right middle temporal gyrus; (3) Non-numerical materials showed stronger activation than Arabic numbers in the left inferior frontal gyrus and the middle temporal gyrus; and (4). Arabic

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Table 1

| Hemisphere | Brain region | BA | Coordinates (X, Y, Z) | Vols. | T value |
|------------|--------------|----|----------------------|-------|---------|
| L          | Superior parietal lobule, PSPL | 7  | −27 −66 51 | 3887 | 10.39   |
| R          | (Middle occipital gyrus) | 17 | −27 −96 6   | 9.29  |         |
| L          | (Inferior parietal lobule, IPS) | 7  | −30 −57 45   | 9.27  |         |
| L          | Inferior frontal gyrus | 44 | −45 6 27    | 791  | 9.25    |
| L          | (Insula) | 47 | −30 21 3     | 8.27  |         |
| L          | Supplementary motor area | 48 | −45 24 27 7  | 7.3   |         |
| L          | Putamen | 36 | −6 9 54     | 259  | 8.07    |
| L          | Lateral prefrontal cortex | 32 | −6 21 48    | 7.05  |         |
| R          | 6         | 9   | 9 54        | 5.22  |         |
| R          | Angular   | 7  | −27 −63 48 114 | 6.24 |         |
| L          | 1         | 0   | 18 95 4.46  |       |         |
| L          | 21        | 9   | −3         | 4.36  |         |
| L          | Thalamus  | 12 | −12 −12 3  | 4.24  |         |

Height threshold: p < .001, uncorrected. Voxel size: 3 × 3 × 3 mm³. Extent threshold: k = 50 voxels. The brain region in the parenthesis refers to the activated region center without maximum peak. IPS: intraparietal sulcus; PSPL: posterior superior parietal lobe. The two brain regions are also specified because they are particularly relevant to numerical processing. Hem., Hemisphere; L: Left; R: Right; BA, Brodmann area; Coordinates (X, Y, Z) are given using the Montreal Neurological Institute (MNI) convention; Vol., volume.

Table 2

| Hemisphere | Brain region | BA | Coordinates (X, Y, Z) | Vols. | T value |
|------------|--------------|----|----------------------|-------|---------|
| R          | Inferior parietal lobule, IPS | 40 | 48 −45 51 | 2769 | 6.58    |
| R          | (Supramarginal gyrus) | 40 | 54 −42 45 | 5.69  |         |
| R          | 40         | −36 | −45 42          | 5.64  |         |
| R          | (Superior parietal lobule, PSPL) | 40 | 42 −48 60 | 5.04  |         |
| L          | Middle frontal gyrus | 9   | −27 30 36 172 | 5.39  |         |
| L          | 9          | −33 | 36 4.87        |       |         |
| L          | 45         | −22 | 33 5.27        |       |         |
| L          | Middle frontal gyrus | 46 | 39 −24 24 707 | 6.06  |         |
| R          | 45         | 39 30 | 5.93  |         |
| L          | Inferior frontal gyrus | 44 | 57 9 27 69 4.05 |       |         |
| R          | 44         | 54 9 | 18 3.97        |       |         |
| L          | Precentral gyrus | 44 | 48 6 30 | 3.48  |         |
| R          | Precentral gyrus | 6  | −3 −54 466 | 4.75  |         |
| R          | (Superior frontal gyrus) | 6 | 27 0 54 4.49 |       |         |
| R          | 6          | −27 −9 48 438 | 4.38  |         |
| L          | Cerebellum | 19 | −27 −63 27 4.23 |       |         |
| L          | −27         | −72 | −54 4.13      |       |         |
| R          | Hippocampus | 24 | −33 9 | 64 4.49 |       |         |
| L          | Insula     | 48 | −21 24 12 63 | 3.79  |         |
| L          | 48         | −21 15 | 18 3.61 |       |         |

Height threshold: p < .008, uncorrected. Extent threshold: k = 50 voxels. Voxel size: 3 × 3 × 3 mm³. The brain region in the parenthesis refers to the activated brain region center without maximum peak. IPS: intraparietal sulcus; PSPL: posterior superior parietal lobe. Hem., Hemisphere; L: Left; R: Right; BA, Brodmann area; Coordinates (X:Y:Z) are given using the Montreal Neurological Institute (MNI) convention; Vol., volume.
Greater activation for numbers relative to the word materials:

- Conjunction
- Arab. > Geom.
- Arab. > Alg.
- Arab. > Ling.
- Arab. > Tool

Greater activations for word materials relative to numbers:

- Conjunction
- Geom. > Arab.
- Alg. > Arab.
- Ling. > Arab.
- Tool > Arab.

Fig. 2. The contrasts of numbers and word materials (i.e., geometric terms, algebraic terms, linguistic terms and tool words). Height threshold: $p < .008$, uncorrected. Extent threshold: $k = 50$ voxels. Voxel size: $3 \times 3 \times 3 \text{ mm}^3$. Arab: Arabic numbers; Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms. The left of picture is the left of brain.

Greater activation for geometric terms relative to linguistic terms and tool words:

- Conjunction
- Geom. > Ling.
- Geom. > Tool

Greater activation for algebraic terms relative to linguistic terms and tool words:

- Conjunction
- Alg. > Ling.
- Alg. > Tool

Fig. 3. The contrasts of mathematical terms and non-mathematical word materials (i.e., linguistic terms and tool words). Height threshold: $p < .008$, uncorrected. Extent threshold: $k = 15$ voxels. Voxel size: $3 \times 3 \times 3 \text{ mm}^3$. Arab: Arabic numbers; Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms. The left of picture is the left of brain.

Greater activation for numbers relative to the word materials:

- Conjunction
- Arab. > Geom.
- Arab. > Alg.
- Arab. > Ling.
- Arab. > Tool

Greater activations for word materials relative to numbers:

- Conjunction
- Geom. > Arab.
- Alg. > Arab.
- Ling. > Arab.
- Tool > Arab.

The intraparietal sulcus and the processing of mathematical terms

As expected, geometric terms had greater activation than algebraic terms, linguistic terms, and tool words in the left inferior parietal cortex as shown from the two sets of ROI analyses. One explanation of these results lies in the neural basis of mental images of geometric figures. Previous studies have shown that words referring to spatial processing might also extend to the PSPL. Algebraic terms did not elicit greater activation at the horizontal IPS regions than did linguistic terms and tool words. This result is contrary to our expectation. It is possible that algebraic terms did not activate sufficiently mental representations of numbers. That is, the processing algebraic terms (e.g., “fraction”) might not have activated the processing of related numerical exemplars (e.g., “$\frac{1}{2}, \frac{1}{3}, \ldots$”). This result explains why arithmetic facts and conceptual algebraic knowledge have been found to be dissociated at the IPS (Delazer and Benke, 1997; Hittmair-Delazer et al., 1994; Warrington, 1982).

The area and the processing of the mathematical terms

Non-numerical words elicited more activations in the left frontal lobe and the temporal lobe than did Arabic numbers. These two brain regions are critical for language processing (e.g., Chee et al., 1999; Petersen et al., 1990; Poldrack et al., 1999; Price et al., 1996; Tan et al., 2000). In terms of the role of the language areas in the processing of mathematical terms, two other issues need to be discussed. First, a number of the mathematical terms have alternative non-mathematical meanings. For example, “$+$” in Chinese has several meaning, including “sum”, “and”, “harmony”, and “peace”. Although...
subjects were instructed to focus on the mathematical meanings of these terms, we could not rule out automatic activation of these words’ alternative meanings. Those meanings would activate the language areas. Furthermore, to discriminate among the alternative meanings of a mathematical word in order to judge its semantic proximity with another word would require more cognitive control, which involves, among other regions, the middle temporal and inferior frontal areas (Whitney et al., 2011). Therefore, an alternative explanation of our results regarding algebraic terms may be the involvement of their multiple meanings. Future research needs to specifically test this alternative hypothesis.

Second, Chinese is a logographic script that is much more spatially complicated than alphabetical scripts. In this experiment, all stimuli except for Arabic numerals were written in Chinese. It is plausible that the script differences might offer another confound in the large differences between Arabic numbers and the other materials. However, Wei et al. (2011) recently found that Chinese number words had the same activation at the IPS as Arabic numbers. Therefore, our results did not seem to be driven by differences in scripts. We may then speculate that Western subjects would show a similar pattern of results as ours. Indeed, as reviewed earlier, neuropsychological studies of Westerners have documented a dissociation between mathematical terms and numerical processing (Delazer and Benke, 1997; Delazer et al., 1998; Pesenti et al., 2000; Tucha et al., 1997; Van Harskamp et al., 2002; Zhou et al., 2007). For example, several studies have found that injuries to the angular gyrus or even the removal of this brain region did not affect subjects’ performance on multiplication (e.g., Delazer and Benke, 1997; Tucha et al., 1997; Van Harskamp et al., 2002). Zhou et al. (2007) found that multiplication did not have greater activation than addition in the angular gyrus, only in the superior temporal gyrus, precentral gyrus and supplementary motor area. Andres et al. (2011) also found no activation in the angular gyrus for multiplication relative to subtraction, letter reading or even fixation. This region has also been found to be susceptible to task difficulty, that is, easy arithmetic problems consistently elicit greater activation than difficult arithmetic problems (e.g., Grabner et al., 2009; Jost et al., 2011; Stanescu-Cosson et al., 2000; Zhou et al., 2007).

**Brain organization of numerical processing**

Previous research has clearly documented the role of the IPS in number processing (e.g. Arsalidou and Taylor, 2011; Dehaene et al., 1999; see a review by Dehaene et al., 2003). Our study extended it to include geometric terms. The IPS’s function in processing numbers and spatial information may be one of the same because quantity of numbers has spatial representations as demonstrated by the mental number line (e.g. Zorzi et al., 2002). It seems that geometric terms can activate the IPS because these terms can elicit the mental images of geometric figures.

We also found that numbers also showed greater activations in the frontal gyrus than non-numerical materials. These activations
may have been due to the differential need for some general-purpose cognitive functions such as working memory (Arsalidou and Taylor, 2011; Christoff and Gabrieli, 2000; Owen et al., 2005). The activation in the middle frontal gyri was attributed to working memory and procedural complexity (Delazer et al., 2003; Fehr and Herrmann, 2007; Kong et al., 2005; Simon et al., 2002; Zhou et al., 2007). Arsalidou and Taylor’s meta-analysis (2011) found that solving calculation tasks elicited ALE (activation likelihood estimation) values in more prefrontal areas than solving number tasks. This difference could also be explained in terms of the working memory load. According to Dehaene and Cohen’s triple-code model, the prefrontal cortex is also responsible for strategy choice and planning (Dehaene and Cohen, 1997). The greater activation for numerical processing relative to non-numerical materials in the prefrontal cortex is consonant with the greater activation in the IPS, which may reflect the recruitment of working memory on the numerical magnitude information or visuospatial codes of numbers.

Brain laterality for numerical processing is a long-standing topic. Arsalidou and Taylor’s (2011) meta-analysis of brain areas for calculations showed that the laterality of numerical processing differed across operations, with addition showing left laterality in the parietal cortex and multiplication right laterality. They thought that lateralization in the parietal cortex (also including BA 46) would be affected by the strategy adopted for solving each operation. That is, addition
and subtraction with the strategies of counting and transformation (e.g., Imbo and Vandierendonck, 2007) would be more leftward, but automatized multiplication would be more rightward. The current study showed clear bilateralization at the parietal cortex and right lateralization at the prefrontal cortex (BA 46) for numbers, but left lateralization for all materials involving words. According to the differential strategies explanation, numerical processing right lateralization at the prefrontal cortex (BA 46) for numbers, but automatized multiplication would be more rightward. The current study showed clear bilateralization at the parietal cortex and right lateralization at the prefrontal cortex (Casasanto, 2003; Dehaene et al., 1993; Kuo et al., 2001, 2004; Tan et al., 2000, 2005; Zorzi et al., 2002).

Summary

Our study confirmed that numbers are processed in the bilateral IPS and prefrontal cortex. In addition, we found that geometric terms elicited more left IPS activations than did algebraic terms and non-mathematical words. Like the non-number words (e.g., linguistic terms and tool words), geometric and algebraic terms are also processed in the general language areas, including the left middle temporal gyrus and the left inferior frontal gyrus. More research is needed to understand how the processing of various aspects of mathematical knowledge (number processing, memory of number facts, knowledge of terms for different areas of mathematics such as geometry and algebra, rules and strategies) is distributed across the brain regions.

Appendix A. Terms, tool words and numbers used in the current study

A.1. Geometric terms.

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|--------------|---------------|---------|--------------|---------------|---------|
| 坐标           | zuò bāo       | Coordinate | 平角          | píng ji o     | Straight angle |
| 周角           | zhōu ji o     | Perigon | 底面          | dī miàn       | Undersurface |
| 正方形         | zhèng fāng xíng | Square | 面积          | miàn jì       | Area |
| 固柱(体)        | yùn zhù t    | Cylinder | 半径          | bàn jìng      | Radius |
| 固形           | yùn xíng     | Circle  | 点            | diàn         | Dot |
| 固心           | yùn xīn      | Center of a circle | 直径          | zhí jìng     | Diameter |
| 外接           | wài jiè      | Circumscribed | 侧切          | cè qiè       | Inscribe |
| 同心圆         | tóng xīn yuán | Concentric circles | 侧环          | yuán huán    | Donut |
| 射线           | shè xiàn     | Radial  | 侧线          | zhí xiàn     | Straight line |
| 扇形           | shàn xíng    | Sector | 余弦          | yú xián     | Complementary angle |
| 全等           | quán dèng    | Congruent | 相似          | xiāng sì     | Similar |
| 曲线           | qū xiàn     | Curve | 主轴          | zhǔ zhóu     | Perpendicular |
| 几面           | jǐ miàn     | Curved surface | 轴向          | zhóu xiàng   | Intersect |
| 球体           | qióu t       | Sphere | 中心          | zhōng xīn   | Cube |
| 平行线         | píng xíng xiàn | Parallel | 母线          | mǔ xiàn     | Perimeter |
| 内角           | nèi ji o    | Interior angle | 形状          | xíng zhào    | Perpendicular |
| 梯形           | tí xíng    | Rhombus | 相交          | xiāng jiāo  | Intersect |
| 梯             | tíng       | Aris | 立方体        | lì fāng tì  | Cube |
| 矩形           | jù xíng    | Rectangle | 外角          | wài ji o    | Exterior angle |
| 截面           | jié miàn   | Section | 凸面          | tū miàn     | Convexity |
| 弧长           | hú cháng   | Arc length | 凸角          | tū ji ào    | Vertex angle |
| 弧             | hú         | Arc | 体积          | tǐ jī       | Volume |
| 高             | gāo        | Height | 面            | miàn        | Face |
| 层             | céng       | Layer | 边长          | biān zhǎng  | Side |
| 垂直           | chuí zhí  | Vertical | 相离          | xiāng lì    | Opening |
| 长方体         | cháng fāng t | Cuboid | 相离          | xiāng lì    | Ellipse |
| 补角           | bǔ ji o    | Supplementary angle | 补行          | bù xíng    | Parallel |
| 凹面           | āo miàn    | Concave side | 方形          | fāng xíng  | Square |
| 象限           | xiàng xiàn | Quadrant | 球面          | qiú miàn    | Sphere |

A.2. Algebraic terms.

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|--------------|---------------|---------|--------------|---------------|---------|
| 自然数         | zì rán shù  | Natural number | 有理数        | yǒu lǐ shù    | Rational number |
| 质数           | zhì shù      | Prime number | 客数          | kè shù       | Real number |
| 指数           | zhì shù      | Exponent | 有小数        | yǒu xiǎo shù | Decimal fraction |
| 正数           | zhèng shù    | Positive number | 除数          | chú shù      | Divide |
| 齐数           | zhí shù      | Integer | 异数          | yì shù       | Multiplier |
| 真分数         | zhēn fēn shù | Proper fraction | 众数          | zhòng shù    | Mode |
| 余数           | yú shù      | Remainder | 减数          | jiǎn shù     | Subtractor |
| 因数           | yīn shù    | Factor | 分母          | fèn          | Denominator |
| 序数           | xù shù      | Ordinal number | 被除数        | bèi chú shù  | Dividend |

(continued on next page)
### Appendix A.2

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|--------------|---------------|---------|--------------|---------------|---------|
| 商           | shāng         | Quotient| 小           | xiǎo          | Decimals|
| 幕           | mù           | Power   | 等比         | děng bǐ       | Equal ratio|
| 均数         | jūn shù      | Mean    | 平方         | píng fāng    | Square |
| 绝对值       | jué duì zhì   | Absolute value | 变量         | biàn lǎng     | Variable|
| 保分数       | jiǎ fèn zhù  | Improper fraction | 减         | jiǎn          | Subtract|
| 加数         | jiā shù      | Addend  | 乘         | chéng        | Multiply|
| 积           | jī           | Product | 算数         | suàn shù     | Function|
| 和           | hé           | Sum     | 无理数       | wú lǐ        | Irrational number|
| 会数         | huì shù      | Composite number | 虚数        | xū          | Imaginary number|
| 负数         | fù shù     | Negative number | 平方数       | píng fāng   | Square number|
| 分子         | fèn zì      | Numerator | 正整数       | zhèng zhèng shù | Positive integer|
| 分数         | fēn shù    | Fraction | 倍数         | bèi shù       | Base number|
| 等差         | děng chā    | Equal difference | 偶数         | ǒu          | Even number|
| 除数         | chú shù     | Divisor | 约数         | yuē          | Approximate number|
| 率           | lǜ           | Rate    | 开方数       | kāi fāng       | Root|
| 常量         | cháng lǐng | Constant | 倒数         | dào        | Reciprocal|
| 差           | chā           | Difference | 恒式         | hénɡ shì     | Equality|
| 比例         | bǐ lì     | Ratio | 开方         | kāi fāng     | Root|
| 倍数         | bèi shù     | Multiple | 小数         | xiǎo          | Odd number|
| 对数         | duì shù     | Logarithm | 奇数        | jī shù      | Odd number|

### A.3. Linguistic terms.

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|--------------|---------------|---------|--------------|---------------|---------|
| 主语         | zhǔ yǔ       | Subject | 窃           | qiè          | Note |
| 杂文         | zuān wén    | Essay   | 会意         | huì yì      | Knowing |
| 增       | zēng        | Elegant | 悄           | qiāo          | Note |
| 象征         | xiàng zhēng | Symbol | 律诗         | lǜ shī     | Eight line poem|
| 象形         | xiàng xíng | Representation | 议论        | yì lùn      | Discuss|
| 读音         | dú yīn     | Predicate | 议        | yì          | Word|
| 唐诗         | táng shī | Tang poem | 雅词         | yǎ cí         | Allegory|
| 宋词         | sòng cí     | Song poems | 翅词         | chì cí        | Letter|
| 说柄         | shuō bǐng | Illustration | 对偶         | duì ǒu      | Antithesis|
| 时态         | shí tài     | Tense   | 开方数       | kāi fāng     | Root|
| 诗           | shī       | Poem    | 小数         | xiǎo          | Odd number|
| 神话         | shén huà | Mythology | 同义       | tóng yì       | Synonymy|
| 日记         | rì jì       | Diary   | 家词         | jiā cí      | Adverb|
| 统比         | tǒng bǐ   | Parallelism | 国词        | guó cí       | Hokkien|
| 名词         | míng cí     | Noun    | 汉词         | hàn cí       | Metrical verse|
| 绝句         | jué jù   | Four line poem | 唐词       | táng cí  | Local expression|
| 句子         | jù zì     | Sentence | 现代词       | xiàn dài cí | Rhetorical question|
| 近义         | jìn yì    | Synonymy | 古词         | gǔ cí       | Contrast|
| 介词         | jiè cí      | Preposition | 正体       | zhèng tǐ    | Analogy|
| 广东话       | guǎng dōng huà | Cantonese | 杂剧        | zá jù        | Poetic drama|
| 古体诗       | gǔ tǐ shī | Pre-Tang poetry | 学赋        | xué fù      | Han fu|
| 方言         | fāng yán | Dialect | 腠词         | tóu cí      | Play|
| 对比         | duì bǐ    | Contrast | 偏义词       | piān yì cí | Conjunction|
| 动词         | dòng cí    | Verb | 近义词         | jìn yì cí    | Semantic|
| 定语         | dìng yǔ   | Attribute | 普通话        | pǔ tōng huà | Mandarin|
| 其他         | qí zhé     | Object | 演义词       | yuán yì cí | Prose poem|
| 名记         | míng jì | Notes | 偏正词       | piān zhèng cí | Repetition|

### A.4. Tools and other common objects.

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|--------------|---------------|---------|--------------|---------------|---------|
| 医药         | yī yào      | Medicine | 医疗         | yī liáo   | Blower|
| 小号         | xiǎo hào   | Trumpet | 灌篮         | guàn lán   | Horn |
| 虚           | xiū       | Xiao   | 哨          | shào        | Zurna|
| 战            | zhàn       | War    | 炮          | pào       | Shovel|
| 械           | xiè       | Weapon | 机          | jī       | Pliers|
| 手机         | shǒu jī     | Cellphone | 灯          | dēng     | Lamp|
| 策            | cè        | Sheng | 盘          | pán       | Ladle|
| 铁笔         | tiě bǐ     | Pencil | 笔          | bǐ        | Koto|
| 望远镜       | wàng yuǎn jìng | Telescopes | 折刀        | zhé dāo   | Gong|
| 螺丝刀       | luó sī dāo | Screwdriver | 折刀        | zhé dāo   | Knife|

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Appendix B. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.neuroimage.2011.12.006.

References

Alivisatos, B., Petrides, M., 1997. Functional activation of the human brain during mental rotation. Neuropsychologia 35 (2), 111–118.
Anders, M., Polgrims, B., Michaux, N., Olivier, E., Penenti, M., 2011. Role of distinct parietal areas in arithmetic: an fMRI-guided TMS study. NeuroImage 54 (4), 3048–3056.
Ansari, D., Dhital, B., Siong, S.C., 2006. Parametric effects of numerical distance on the magnitude. Neuropsychologia 45 (6), 1413–1420.
Bennett, B., Cappelletti, M., Kopelman, M., 2001. Category specific advantage for numbers in verbal short-term memory: evidence from sentence-picture matching. Neuropsychologia 39 (12), 1725–1738.
Bennett, B., Cappelletti, M., Potter, B., 2002. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 40 (10), 1775–1783.
Bennett, B., Cappelletti, M., Potter, B., 2003. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 41 (1), 131–141.
Bennett, B., Cappelletti, M., Potter, B., 2004. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 42 (12), 1539–1546.
Bennett, B., Cappelletti, M., Potter, B., 2005. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 43 (12), 1633–1635.
Bennett, B., Cappelletti, M., Potter, B., 2006. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 44 (12), 2075–2080.
Bennett, B., Cappelletti, M., Potter, B., 2007. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 45 (12), 2438–2446.
Bennett, B., Cappelletti, M., Potter, B., 2008. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 46 (12), 3486–3492.
Bennett, B., Cappelletti, M., Potter, B., 2009. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 47 (12), 2493–2499.
Bennett, B., Cappelletti, M., Potter, B., 2010. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 48 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2011. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 49 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2012. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 50 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2013. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 51 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2014. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 52 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2015. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 53 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2016. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 54 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2017. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 55 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2018. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 56 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2019. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 57 (12), 3484–3490.
Bennett, B., Cappelletti, M., Potter, B., 2020. How specific is the magnitudes advantage for numbers in verbal short-term memory. Neuropsychologia 58 (12), 3484–3490.
Kadosh, R.C., Henik, A., Rubinstein, G., Mohr, H., Dori, H., van de Ven, V., Zorzi, M., Hendler, T., Goebel, R., Linden, D.E.J., 2005. Are numbers special? The comparison systems of the human brain investigated by fMRI. Neuropsychology 43 (9), 1238–1248.

Kadosh, R.C., Kadosh, K.C., Kaas, A., Henik, A., Goebel, R., 2007. Notation-dependent and independent representations of numbers in the parietal lobes. Neuron 53 (2), 307–314.

Kadosh, R.C., Lammertyn, J., Izard, V., 2008. Are numbers special? An overview of chromatic, neuroimaging, developmental and comparative studies of magnitude representation. Prog. Neurobiol. 84 (2), 132–147.

Knops, A., Nuerk, H.C., Fimm, B., Vohn, R., Willmes, K., 2006. A special role for numbers in working memory? An fMRI study. NeuroImage 29 (1), 1–14.

Kong, J., Wang, C., Kwong, K., Vangel, M., Chua, E., Collobb, R., 2005. The neural substrate of arithmetic operations and procedure complexity. Cogn. Brain Res. 22 (3), 397–405.

Kucian, K., Loeveneker, T., Dietrich, T., Dosch, M., Martin, E., Von Aster, M., 2006. Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. Behav. Brain Funct. 2 (1), 31–47.

Kuo, W.J., Yeh, T.C., Duanii, J.R., Wu, Y.T., Ho, L.T., Hung, D., Zeng, O.J.L., Hsieh, J.C., 2001. A left-lateralized network for reading Chinese words: a 3 T fMRI study. Neurouige 12 (18), 3997–4001.

Kuo, W.J., Yeh, T.C., Lee, J.R., Chen, L.F., Lee, P.L., Chen, S.S., Ho, L.T., Hung, D., Zeng, O.J.L., Hsieh, J.C., 2004. Orthographic and phonological processing of Chinese characters: an fMRI study. NeuroImage 21 (4), 1721–1731.

Le Clec’h, G., Dehaene, S., Cohen, L., Mehler, J., Dupoux, E., Poline, J.B., Lehéricy, S., van de Moorte, P.F., Le Bihan, D., 2000. Distinct cortical arcs for names of numbers and body parts independent of language and input modality. NeuroImage 12 (4), 381–391.

Lee, K.M., 2000. Cortical areas differentially involved in multiplication and subtraction: a functional magnetic resonance imaging study and correlation with a case of selective acalculia. Ann. Neurol. 48 (4), 657–661.

Lemer, C., Dehaene, S., Spelke, E., Cohen, L., 2003. Approximate quantities and exact knowledge. Nature 379 (6566), 649–652.

Molko, N., Cachia, A., Riviere, D., Mangin, J.F., Brunandt, M., LeBihan, D., Cohen, L., Dehaene, S., 2003. Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin. Neuro Report 40 (4), 847–858.

Molko, N., Cachia, A., Riviere, D., Mangin, J., Brunandt, M., LeBihan, D., Cohen, L., Dehaene, S., 2004. Brain anatomy in Turner syndrome: evidence for impaired socio and spatial Ncual numerical systems. Cereb Cortex 14 (8), 840–850.

Mummery, C., Patterson, K., Hodges, J., Price, C., 1998. The mental representation of spatial descriptions. Mem. Cognit. 10 (2), 181–187.

Morton, A., Wiggs, C.L., Ungerleider, L.G., Haxby, J.V., 1996. Neural correlates of category-specific knowledge. Nature 379 (6566), 649–652.

Owen, A.M., McMillan, K., Laird, A.R., Bullmore, E., 2005. N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. Hum. Brain Mapp. 25 (5), 46–59.

Pesenti, M., Thooux, M., Seron, X., Volder, A.D., 2000. Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: An PET study. J. Cogni. Neurosci. 12 (3), 461–479.

Peterson, S.E., Fox, P.T., Snyder, A.Z., Raichle, M.E., 1990. Activation of extrastriate and frontal cortical areas by visual words and word-like stimuli. Science 249 (4972), 1041–1044.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., Dehaene, S., 2004. Tuning curves for approximate numerosity in the human intraparietal sulcus. Neuro Report 14 (3), 547–555.

Piazza, M., Pinel, P., Le Bihan, D., Dehaene, S., 2007. A magnitude code common to numerosities and number symbols in human intraparietal cortex. Neuro Report 53 (2), 293–305.

Poldrack, R.A., Wagner, A.D., Prull, M.W., Desmond, J.E., Glover, G.H., Gabrieli, J.D.E., 1999. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. NeuroImage 10 (1), 15–35.

Prado, J., Mutreja, R., Zhang, H., Mehta, R., Desroches, A.S., Minas, J.E., Booth, J.R., 2011. Distinct representations of subtraction and multiplication in the neural systems for numerosity and language. Hum. Brain Mapp. 32 (11), 1932–1947.

Price, C.J., Wise, R., Frackowiak, R., 1996. Demonstrating the implicit processing of visually presented words and pseudowords. Cereb. Cortex 6 (1), 62–70.

Rorden, C., Karnath, H.O., Bonilha, L., 2007. Improving lesion–symptom mapping. J. Cogni. Neurosci. 19 (7), 1081–1088.

Rutzer, S., Kucian, K., Martin, E., Von Aster, M., Klaver, P., Loeveneker, T., 2008. Optimized voxel-based morphometry in children with developmental dyscalculia. NeuroImage 39 (1), 417–422.

Seghier, M.L., 2008. Laterality index in functional MRI: methodological issues. Magn. Reson. Imaging 26 (3), 594–601.

Shuman, M., Kanwisher, N., 2004. Numerical magnitude in the human parietal lobe: tests of representational generality and domain specificity. Neuron 44 (3), 557–569.

Simon, O., Mangin, J.F., Cohen, L., Le Bihan, D., Dehaene, S., 2002. Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. Neuron 33 (3), 475–487.

Springer, J.A., Binder, J.R., Hammeke, T.A., Swanson, S.J., Frost, J.A., Bellgowan, P.S.F., Brewer, C.C., Perry, H.M., Morris, G.L., Mueller, W.M., 1999. Language dominance in neurologically normal and epilepsy subjects. Brain 122 (11), 2033–2045.

Stanescu-Cossion, R., Pinel, P., van de Mooterpe, P.F., Le Bihan, D., Cohen, L., Dehaene, S., 2000. Understanding dissociations in dyscalculia: a brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. Brain 123 (11), 2240–2255.

Takayama, Y., Sugishita, M., Akiyoshi, I., Kimura, J., 1994. Isolated acalculia due to left parietal lesion. Arch. Neurol. 51 (3), 286–291.

Tan, L.H., Spinks, J.A., Gao, J.H., Liu, H.L., Perfetti, C.A., Xiong, J.H., Stofer, K.A., Pu, Y.L., Liu, Y.J., Fox, P.T., 2000. Brain activation in the processing of Chinese characters and words: a functional MRI study. Hum. Brain Mapp. 10 (1), 16–27.

Tan, L.H., Laird, A.R., Li, K., Fox, P.T., 2005. Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: a meta-analysis. Hum. Brain Mapp. 25 (1), 83–91.

Thioux, M., Pesenti, M., Costes, N., De Volder, A., Seron, X., 2005. Task-independent semantic activation for numbers and animals. Cogn. Brain Res. 24 (2), 284–290.

Tucha, O., Steup, A., Smely, C., Lange, K.W., 1997. Toe agnosia in Gerstmann syndrome. J. Neurol. Neurosurg. Psychiatry 63 (3), 399–403.

van Harskamp, N.J., Rudge, P., Cipolotti, L., 2002. Are multiplication facts implemented by the left supramarginal and angular gyri? Neuropsychologia 40 (11), 1786–1793.

Vingerhoets, G., Santens, P., Van Laere, K., Lahorte, P., Dierckx, R.A., De Reuck, J., 2001. Regional brain activity during different paradigms of mental rotation in healthy volunteers: a positron emission tomography study. NeuroImage 13 (2), 381–391.

Warrington, E., 1982. The fractionation of arithmetical skills: a single case study. Q. J. Exp. Psychol. A 34 (1), 31–51.

Wei, W., Zhang, H., Chen, C.S., Zhou, X.L., 2011. Neural dissociations in quantity processing of single-digit addition and multiplication. NeuroImage 35 (2), 871–880.

Zorzi, M., Priftis, K., Umilta, C., 2002. Brain damage — neglect disrupts the mental number line. Nature 417 (6885), 138–139.