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# 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.



## 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., 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; Lemer et al., 2003; Zamarian et al., 2006). Second, functional MRI studies have systematically shown that numerical processing elicits greater activation in the parietal lobule 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 showed to be associated with structural abnormalities in the IPS regions (e.g., Isaacs 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 with verbal processing of numbers, and the posterior superior parietal lobule with attentional processes. The brain regions around the bilateral intraparietal sulcus are relatively specific to the number-related processes, but the regions for verbal and attentional processes have more general functions. In addition to the parietal cortex, the prefrontal cortex has also been found to be critical for numerical processing (e.g., Arsalidou and Taylor, 2011; Fehr and Herrmann, 2007; Ischebeck et al., 2006; Kong et al., 2005), most likely because it 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

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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 “$\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, …”, 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 lobule, 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 permutated 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 × 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

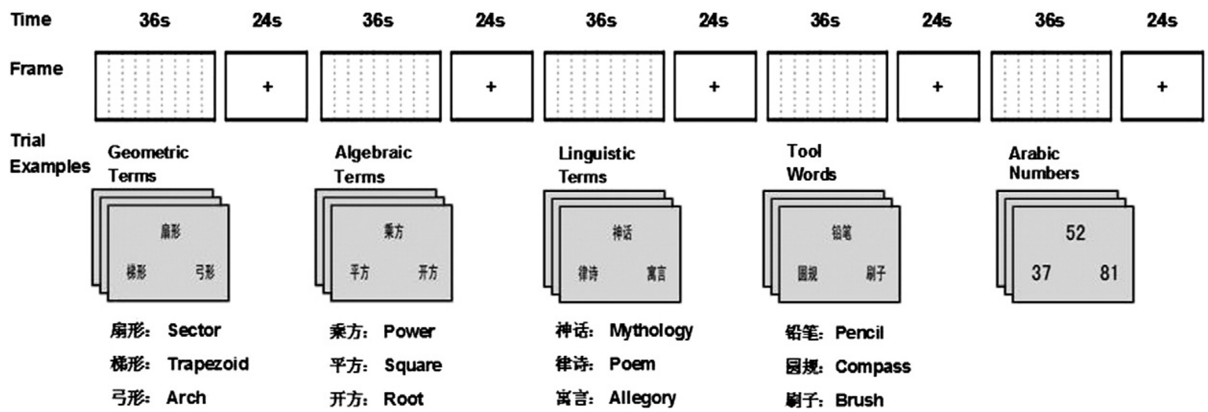


**Fig. 1.** The experimental procedure of a run and sample trials in the current study. Each run lasted 5 min. It contained five experimental blocks (one block of nine trials for each type of materials) and five blocks of fixation (the baseline task). Each experimental block lasted for 36 s, and each fixation block for 24 s. The order of the blocks was arranged in the Latin square design among the three runs to avoid having the same condition occurring at the same position in different runs.

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, the left angular gyrus (AG) for verbal processing in numerical 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 MRIcron 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 by Arsalidou 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.ansir.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

**Table 1**
Loci showing significant activations based on the conjunction analysis of the five types of materials (i.e., numbers, geometric terms, algebraic terms, linguistic terms and tool words).

| Hem. | Brain region | BA | Coordinates (X, Y, Z) | | | Vol. | T |
|---|---|---|---|---|---|---|---|
| L | Superior parietal lobule, PSPL | 7 | −27 | −66 | 51 | 3887 | 10.39 |
| R | (Middle occipital gyrus) | 17 | 27 | −96 | 6 | | 9.29 |
| | (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 | | 48 | −45 | 24 | 27 | | 7.3 |
| L | Supplementary motor area | 6 | −6 | 9 | 54 | 259 | 8.07 |
| L | | 32 | −6 | 21 | 48 | | 7.05 |
| R | | 6 | 9 | 9 | 54 | | 5.22 |
| R | Angular | 7 | 27 | −63 | 48 | 114 | 6.24 |
| L | Putamen | | −21 | 0 | 18 | 95 | 4.48 |
| L | | | −21 | 9 | −3 | | 4.36 |
| L | (Thalamus) | | −12 | −12 | 3 | | 4.24 |

Height threshold: $p<.001$, uncorrected. Voxel size: $3\times3\times3$ mm$^3$. 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.

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 (XYZ: 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 (XYZ: −21 −57 54), right SPL ROI (XYZ: 18-78 54), left MFG ROI (XYZ: −27 33 36) and right MFG ROI (XYZ: 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

**Table 2**
Loci showing significant activations based on the conjunction analysis of the contrasts of numbers minus word materials (i.e., numbers > geometric terms, numbers > algebraic terms, numbers > linguistic terms, and numbers > tool words) and of the contrasts of word materials minus numbers (i.e., geometric terms > numbers, algebraic terms > numbers, linguistic terms > numbers, and tool words > numbers).

| Hem. | Brain region | BA | Coordinates (X, Y, Z) | | | Vol. | T |
|---|---|---|---|---|---|---|---|
| I. Greater activations for numbers than for word materials | | | | | | | |
| 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 | 39 | | 4.87 |
| L | | 45 | −42 | 33 | 33 | | 2.97 |
| R | Middle frontal gyrus | 46 | 39 | 36 | 24 | 707 | 6.06 |
| R | | 45 | 45 | 39 | 30 | | 5.93 |
| R | | 47 | 39 | 51 | 0 | | 5.09 |
| R | Inferior frontal gyrus | 44 | 57 | 9 | 27 | 69 | 4.05 |
| R | | 44 | 54 | 9 | 18 | | 3.97 |
| R | (Precentral gyrus) | 44 | 48 | 6 | 30 | | 3.48 |
| R | Precentral gyrus | 6 | 33 | −6 | 54 | 466 | 4.75 |
| R | (Superior frontal gyrus) | 6 | 27 | 0 | 54 | | 4.49 |
| R | | 6 | 27 | −9 | 48 | | 4.38 |
| L | Cerebellum | | −42 | −48 | −42 | 162 | 4.56 |
| L | | 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 |
| II. Greater activations for word materials than for numbers | | | | | | | |
| L | Inferior frontal gyrus | 47 | −39 | 36 | −12 | 368 | 5.27 |
| L | | 45 | −54 | 24 | 21 | | 5.23 |
| L | | 45 | −51 | 36 | 6 | | 4.88 |
| L | Middle temporal gyrus | 21 | −63 | −51 | 3 | 178 | 4.85 |
| L | | 21 | −54 | −48 | 0 | | 4.18 |
| L | | 22 | −57 | −36 | 3 | | 3.81 |
| L | Inferior temporal gyrus | 20 | −39 | 6 | −42 | | 2.99 |
| L | Fusiform gyrus | 37 | −42 | −48 | −18 | 58 | 4.95 |
| L | (Cerebellum) | 37 | −30 | −42 | −24 | | 4.54 |
| L | Fusiform gyrus | 20 | −30 | −9 | −39 | 51 | 4.71 |
| L | | 20 | −36 | −15 | −36 | | 3.98 |
| L | Inferior occipital gyrus | 17 | −21 | −102 | −6 | 77 | 4.74 |
| R | Inferior occipital gyrus | 17 | 27 | −102 | −6 | 63 | 5.42 |
| R | Cerebellum | | 18 | −87 | −33 | 160 | 5.31 |

Height threshold: $p<.008$, uncorrected. Extent threshold: $k=50$ voxels. Voxel size: $3\times3\times3$ mm$^3$. The brain region in the parenthesis refers to the activated 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.

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

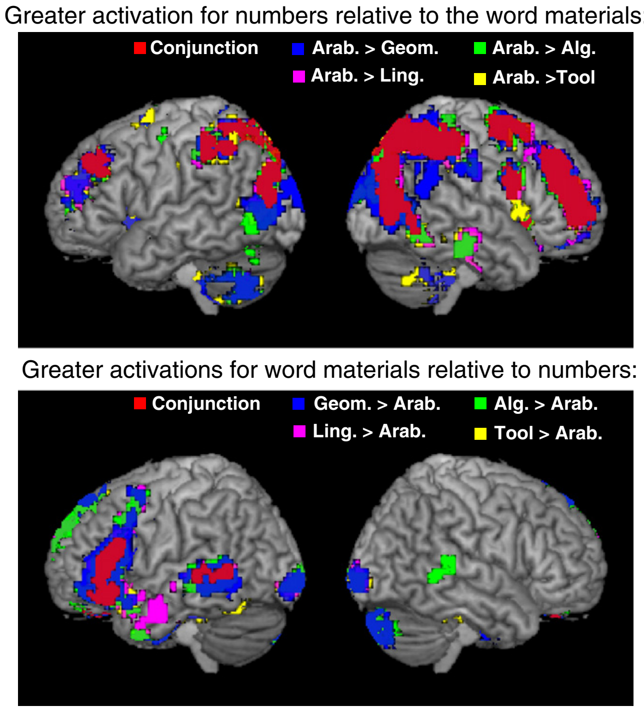


**Fig. 2.** The contrasts of numbers and word materials (i.e., geometric terms, algebraic terms, linguistic terms and tool words). Height threshold: $p<.008$, uncorrected. Extent threshold: $k=50$ voxels. Voxel size: $3\times3\times3$ mm$^3$. Arab: Arabic numbers; Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms. The left of picture is the left of brain.

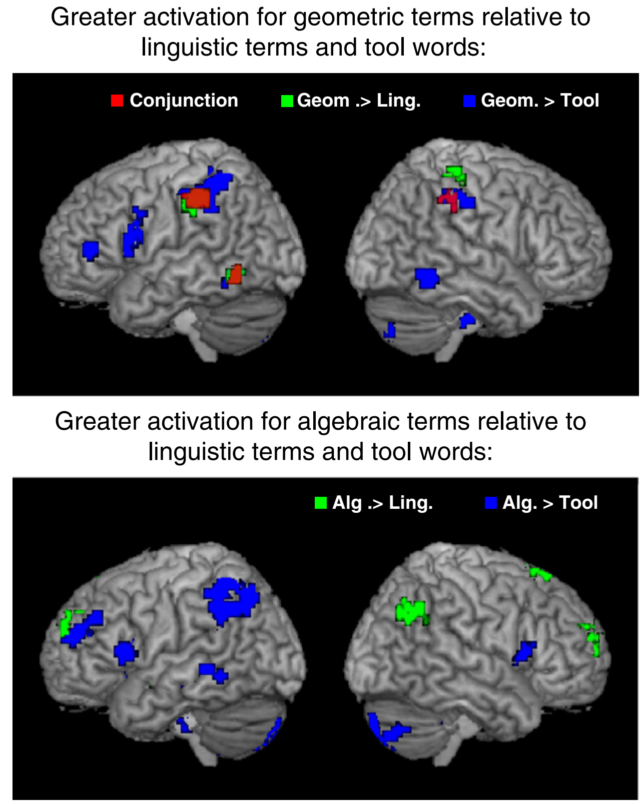


**Fig. 3.** The contrasts of mathematical terms and non-mathematical word materials (i.e., linguistic terms and tool words). Height threshold: $p<.008$, uncorrected. Extent threshold: $k=15$ voxels. Voxel size: $3\times3\times3$ mm$^3$. Arab: Arabic numbers; Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms. The left of picture is the left of brain.

numbers were processed bilaterally, but mathematical terms and tool words showed left dominance. These results suggest that the main brain area for the processing of numbers (the left IPS) seems to be involved in the semantic processing of geometric terms, but not that of other mathematical terms such as algebraic terms. The brain organization for mathematical terms and numbers is discussed in the following sections.

### *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 representations can elicit the processing of spatial figures (e.g., Hayward and Tarr, 1995; Mani and Johnson-Laird, 1982) and that spatial processing is subserved by the parietal cortex (e.g., Hilgetag et al., 2001), especially the inferior parietal lobule (e.g., Alivisatos and Petrides, 1997; Carpenter et al., 1999). Geometric terms as well as numbers also had greater activation than algebraic terms and tool words at the posterior superior parietal lobe as shown in the ROI analysis based on Dehaene et al.'s three parietal circuit model. The processing of numbers and geometrical terms seemed to share common neural resources as visuo-spatial processing. The visuo-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. “$\frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots$”). 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).

**Table 3**
Loci showing significant activation based on conjunction analysis between geometric terms and non-mathematical word materials (i.e., linguistic terms and tool words).

| Hem. | Brain region | BA | Coordinates (X, Y, Z) | | | Vol. | T |
|---|---|---|---|---|---|---|---|
| L | Inferior parietal lobule, IPS | 40 | −54 | −33 | 42 | 45 | 3.63 |
| L | | 40 | −63 | −39 | 42 | | 2.94 |
| R | Supramarginal gyrus | 40 | 66 | −33 | 39 | 15 | 3.17 |
| R | | 40 | 63 | −42 | 45 | | 2.83 |
| L | Inferior temporal gyrus | 37 | −54 | −60 | −9 | 20 | 3.74 |

Height threshold: $p<.008$, uncorrected. Extent threshold: $k=15$ voxels. Voxel size: $3\times3\times3$ mm$^3$. The brain region in the parenthesis refers to the activated region center without maximum peak. IPS: intraparietal sulcus. Hem., Hemisphere; L, Left; R, Right; BA, Brodmann area; Coordinates (X,Y,Z) are given using the Montreal Neurological Institute (MNI) convention; Vol., volume.

### *The language areas and the processing of 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

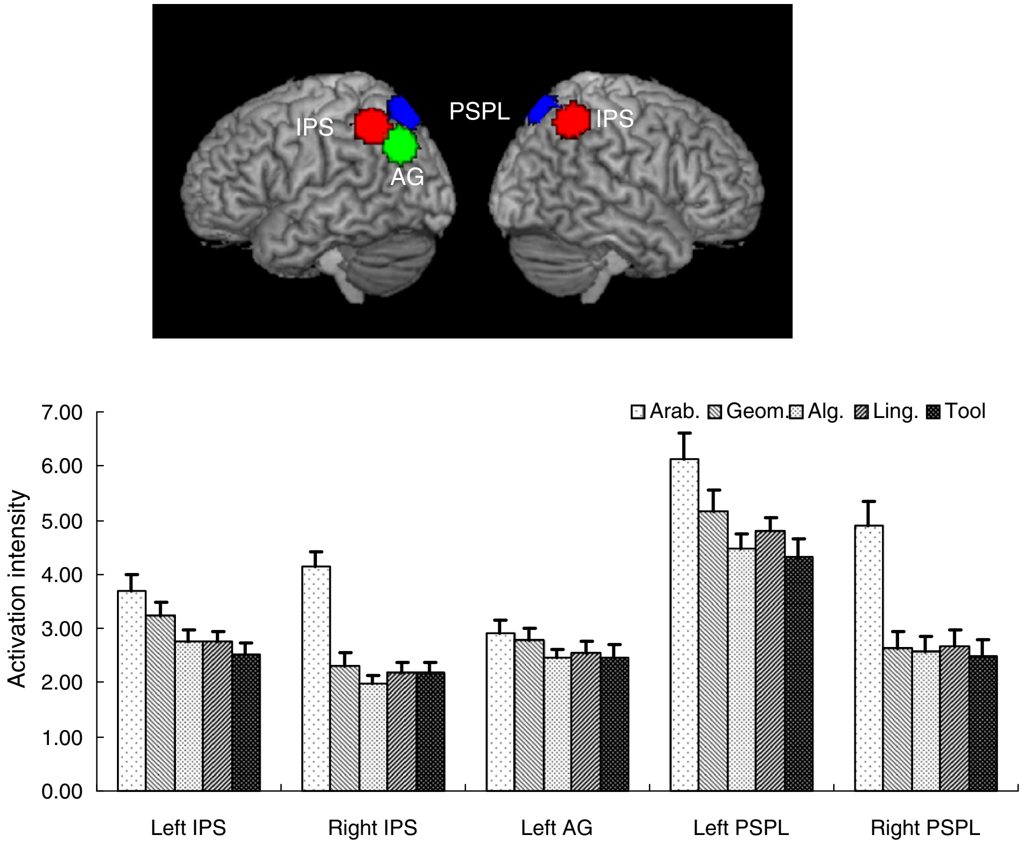


**Fig. 4.** The ROI analyses showed that Arabic numbers elicited greater activation than geometric terms, algebraic terms, linguistic terms, and tool words in the bilateral horizontal intraparietal sulcus (IPS) and the posterior superior parietal lobe (PSPL), and that geometric terms elicited greater activation than algebraic terms and linguistic terms in the left horizontal intraparietal sulcus. The ROIs as shown in the brain map were defined according to Dehaene's three parietal circuit model of numerical processing (Dehaene et al., 2003). The error bars in bar figure indicate standard error of the mean. Arab: Arabic numbers; Geom: geometric terms; Alg: algebraic terms; Ling: linguistic terms; AG: angular gyrus. The left of picture is the left of brain.

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; Hittmair-Delazer et al., 1994; Warrington, 1982).

Dehaene et al.'s three parietal circuit model posits that the angular gyrus supports the verbal representation of numbers (Dehaene et al., 2003). This idea has been supported by some studies (e.g., Chochon et al., 1999; Dehaene et al., 1999; Lee, 2000; Simon et al., 2002), but not others (e.g., Andres et al., 2011; Dehaene et al., 1996; Delazer and Benke, 1997; 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

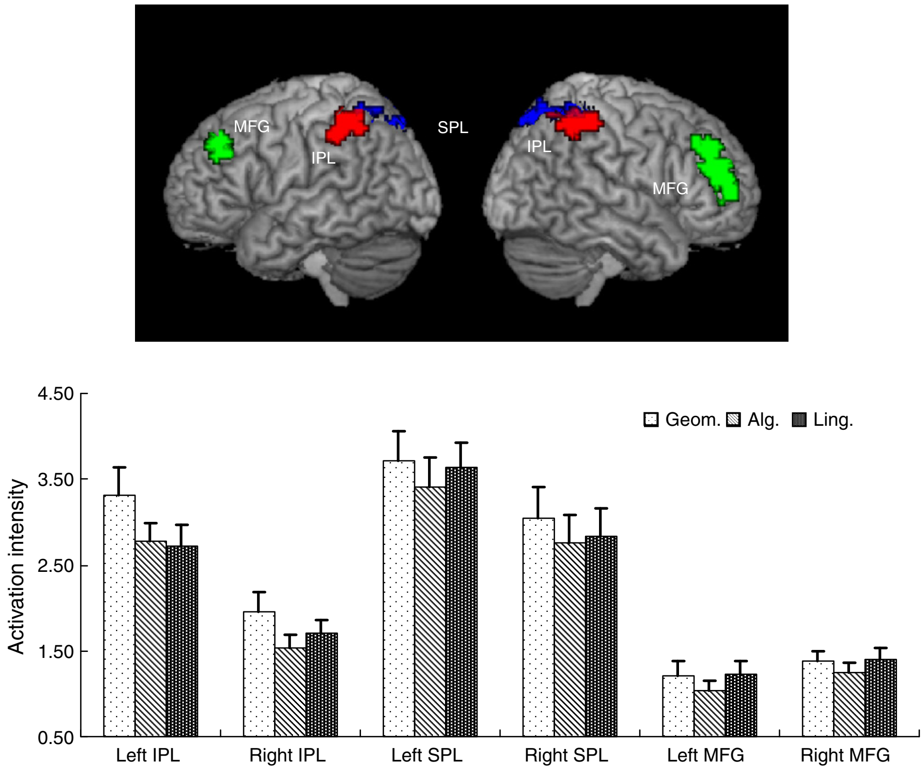


**Fig. 5.** The ROI analyses showed that geometric terms elicited greater activation than both algebraic terms and linguistic terms in the left inferior parietal lobule. The ROIs as shown in the brain map were defined functionally by the "numbers–tool words" contrast in the following six brain regions: the left inferior parietal lobule (IPL), left superior parietal lobule (SPL), left middle frontal gyrus (MFG), right IPL, right SPL and right MFG. Height threshold: $p<.0001$, uncorrected, extent threshold: $k=15$ voxels, and voxel size: $3\times3\times3$ mm$^3$. Error bars indicate standard error of the mean. Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms. The left of picture is the left of brain.

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 visuo-spatial 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

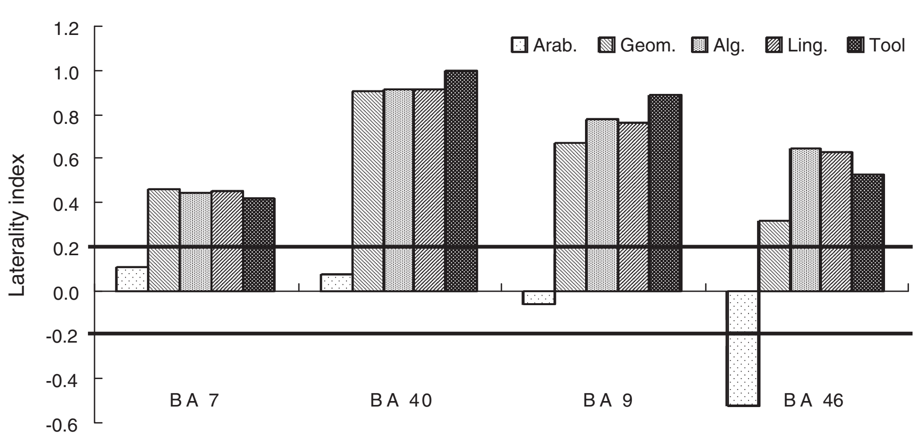


**Fig. 6.** Laterality indices for regions in the parietal and prefrontal cortex. Black horizontal lines represent the criteria of laterality, whereby LI > .20 is deemed left dominant, LI < −.20 as right dominant, and values in-between are considered bilateral. Arab: Arabic numbers, Geom: geometric terms; Alg: algebraic terms; and Ling: linguistic terms.

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 may involve fewer strategies than the word materials. Alternatively, this pattern of laterality reflects the classic left laterality for language processing and right laterality for numbers and spatial processing, particularly in 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.


## Acknowledgments

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## 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 biāo | Coordinate | 平角 | píng ji o | Straight angle |
| 周角 | zhōu ji o | Perigon | 底面 | dǐ miàn | Undersurface |
| 正方形 | zhèng fāng xíng | Square | 面积 | Miàn jī | Area |
| 圆柱(体) | yuán zhù t | Cylinder | 半径 | bàn jìng | Radius |
| 圆形 | yuán xíng | Circle | 点 | diǎn | Dot |
| 圆心 | yuán xīn | Center of a circle | 直径 | zhí jìng | Diameter |
| 外接 | wài jiē | Circumscribed | 内切 | nèi qiē | Inscribe |
| 同心圆 | tóng xīn yuán | Concentric circles | 圆环 | yuán huán | Donut |
| 射线 | shè xiàn | Radial | 直线 | zhí xiàn | Straight line |
| 扇形 | shàn xíng | Sector | 弓形 | gōng xíng | Arch |
| 全等 | quán děng | Congruent | 相似 | xiāng sì | Similar |
| 曲线 | qǔ xiàn | Curve | 梯形 | tī xíng | Trapezoid |
| 曲面 | qǔ miàn | Curved surface | 外角 | wài ji o | Exterior angle |
| 球体 | qíu t | Sphere | 平面 | píng miàn | Plane |
| 平行线 | píng xíng xiàn | Parallel | 周长 | zhōu cháng | Perimeter |
| 内角 | nèi ji o | Interior angle | 垂线 | chuí xiàn | Perpendicular |
| 菱形 | líng xíng | Rhombus | 相交 | xiāng jiāo | Intersect |
| 棱 | léng | Arris | 立方体 | lì fāng tǐ | Cube |
| 矩形 | jǔ xíng | Rectangle | 余角 | yú jiǎo | Complementary angle |
| 截面 | jié miàn | Section | 凸面 | tū miàn | Convexity |
| 弧长 | hú cháng | Arc length | 顶角 | dǐng jiǎo | Vertex angle |
| 弧 | hú | Arc | 体积 | tǐjī | Volume |
| 高 | gāo | Height | 面 | miàn | Face |
| 底 | dǐ | Bottom | 边长 | biān cháng | Side |
| 垂直 | chuí zhí | Vertical | 相离 | xiāng lí | Opening |
| 长方体 | cháng fāng t | Cuboid | 椭圆 | tu  yuán | Ellipse |
| 补角 | bǔ ji o | Supplementary angle | 平行 | píng xíng | Parallel |
| 凹面 | āo miàn | Concave side | 方形 | fāng xíng | Square |
| 象限 | xiàng xiàn | Quadrant | 球面 | qíu 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 | y u l  shù | Rational number |
| 质数 | zhì shù | Prime number | 实数 | shí | Real number |
| 指数 | zh  shù | Exponent | 纯小数 | chún xi o | Decimal fraction |
| 正数 | zhèng shù | Positive number | 除 | chú | Divide |
| 整数 | zhěng shù | Integer | 乘数 | chéng | Multiplier |
| 真分数 | zhēn fēn shù | Proper fraction | 众数 | zhòng | Mode |
| 余数 | yú shù | Remainder | 减数 | ji n | Subtractor |
| 因数 | yīn shù | Factor | 分母 | fēn | Denominator |
| 序数 | xù shù | Ordinal number | 被除数 | bèi chú | Dividend |

(*continued on next page*)

**Appendix A.2** (*continued*)

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|---|---|---|---|---|---|
| 商 | shāng | Quotient | 小数 | xiǎo | Decimals |
| 幂 | mì | Power | 等比 | děng bǐ | Equal ratio |
| 均数 | jūn shù | Mean | 平方 | píng fāng | Square |
| 绝对值 | jué duì zhí | Absolute value | 变量 | biàn liàng | Variable |
| 假分数 | ji fēn shù | Improper fraction | 减 | jiǎn | Subtract |
| 加数 | jiā shù | Addend | 乘 | chéng | Multiply |
| 积 | jī | Product | 函数 | hán | Function |
| 和 | hé | Sum | 无理数 | wú lǐ | Irrational number |
| 合数 | hé shù | Composite number | 虚数 | xū | Imaginary number |
| 负数 | fù shù | Negative number | 平方数 | píng fāng | Square number |
| 分子 | fēn z | Numerator | 正整数 | zhèng zhěng shù | Positive integer |
| 分数 | fēn shù | Fraction | 基数 | jī | Base number |
| 等差 | děng chā | Equal difference | 偶数 | ǒu | Even number |
| 除数 | chú shù | Divisor | 约数 | yuē | Approximate number |
| 乘方 | chéng fāng | Power | 被减数 | bèi jiǎn | Minuend |
| 常量 | cháng liàng | Constant | 倒数 | dào | Reciprocal |
| 差 | chā | Difference | 等式 | děng shì | Equality |
| 比例 | bǐ lì | Ratio | 开方 | kāi fāng | Root |
| 倍数 | bèi shù | Multiple | 向量 | xiàng liàng | Vector |
| 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 | 颂 | sòng | Eulogy |
| 杂文 | zá wén | Essay | 会意 | huì yì | Knowing |
| 雅 | yǎ | Elegant | 阕 | què | Note |
| 象征 | xiàng zhēng | Symbol | 律诗 | lǜ shī | Eight line poem |
| 象形 | xiàng xíng | Representation | 议论 | yì lùn | Discuss |
| 谓语 | wèi yǔ | Predicate | 词 | cí | Word |
| 唐诗 | táng shī | Tang poem | 寓言 | yù yán | Allegory |
| 宋词 | sòng cí | Song poems | 书信 | shū xìn | Letter |
| 说明 | shuō míng | Illustration | 对偶 | duì ǒu | Antithesis |
| 时态 | shí tài | Tense | 代词 | dài cí | Pronoun |
| 诗 | shī | Poem | 段落 | duàn luò | Paragraph |
| 神话 | shén huà | Mythology | 同义 | tóng yì | Synonymy |
| 日记 | rì jì | Diary | 副词 | fù cí | Adverb |
| 排比 | pái bǐ | Parallelism | 闽南话 | mǐn nán huà | Hokkien |
| 名词 | míng cí | Noun | 格律诗 | gé lǜ shī | Metrical verse |
| 绝句 | jué jù | Four line poem | 土语 | tǔ yǔ | Local expression |
| 句子 | jù zǐ | Sentence | 反问 | fǎn wèn | Rhetorical question |
| 近义 | jìn yì | Synonymy | 反衬 | fǎn chèn | Contrast |
| 介词 | jiè cí | Preposition | 比拟 | bǐ nǐ | Analogy |
| 广东话 | guǎng dōng huà | Cantonese | 杂剧 | zá jù | Poetic drama |
| 古体诗 | gǔ tǐ shī | Pre-Tang poetry | 汉赋 | hàn fù | Han fu |
| 方言 | fāng yán | Dialect | 序 | xù | Preface |
| 反语 | fǎn yǔ | Irony | 剧本 | jù běn | Play |
| 对比 | duì bǐ | Contrast | 连词 | lián cí | Conjunction |
| 动词 | dòng cí | Verb | 语义 | yǔ yì | Semantic |
| 定语 | dìng yǔ | Attribute | 普通话 | pǔ tōng huà | Mandarin |
| 宾语 | bīn yǔ | Object | 散文诗 | sǎn wén shī | Prose poem |
| 比喻 | bǐ yù | Metaphor | 反复 | fǎn fù | Repetition |
| 杂记 | zá jì | Notes | 状语 | zhuàng yǔ | Adverbial |

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

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|---|---|---|---|---|---|
| 圆规 | yuán guī | Compass | 吹风机 | chuī fēng jī | Blower |
| 小号 | xiǎo hào | Trumpet | 喇叭 | lǎ bā | Horn |
| 箫 | xiāo | Xiao | 唢呐 | suǒ nà | Zurna |
| 骰子 | tóu zi | Dice | 铲子 | chǎn zi | Shovel |
| 梳子 | shū zi | Comb | 钳子 | qián zi | Pliers |
| 手机 | shǒu jī | Cellphone | 台灯 | tái dēng | Lamp |
| 笙 | shēng | Sheng | 汤勺 | tāng sháo | Ladle |
| 铅笔 | qiān bǐ | Pencil | 古筝 | gǔ zhēng | Koto |
| 耙子 | pá zi | Rake | 锣 | luó | Gong |
| 镊子 | niè zi | Tweezers | 刀子 | dāo zi | Knife |
| 螺丝刀 | luó sī dāo | Screwdriver | 剪刀 | jiǎn dāo | Scissors |

**Appendix A.4** (*continued*)

| Chinese name | Pronunciation | English | Chinese name | Pronunciation | English |
|---|---|---|---|---|---|
| 犁 | lí | Plough | 凿子 | záo zi | Chisel |
| 蜡烛 | là zhú | Candle | 锥子 | zhuī zi | Awl |
| 筷子 | kuài zi | Chopsticks | 电锯 | diàn jù | Electric saw |
| 胡琴 | hú qín | Huqin | 锅铲 | guō chǎn | Spatula |
| 鼓 | gǔ | drum | 订书机 | dìng shū jī | Stapler |
| 钢笔 | gāng bǐ | Pen | 牙刷 | yá shuā | Toothbrush |
| 斧子 | fǔ zi | ax | 起子 | qǐ zi | Screwdriver |
| 粉笔 | fěn bǐ | Chalk | 编钟 | biān zhōng | Chime |
| 电钻 | diàn zuàn | Electric drill | 钢琴 | gāng qín | Piano |
| 锉刀 | Cuò dāo | File | 围棋 | wéi qí | Go |
| 锤子 | chuí zi | Hammer | 电熨斗 | diàn yùn dǒu | Electric iron |
| 菜刀 | cài dāo | Kitchen knife | 琵琶 | pí pa | Chinese lute |
| 裁纸刀 | cái zhǐ dāo | Paper cutter | 刷子 | shuā zi | Brush |
| 杯子 | bēi zi | Cup | 天平 | tiān píng | Balance |
| 扳手 | bān shǒu | Wrench | 琴 | qín | Lyre |
| 尺子 | chǐ zi | Ruler | 绳子 | shéng zi | Rope |
| 笛子 | dí zi | Flute | 拖把 | tuō ba | Mop |
| 麻将 | má jiàng | Mahjong | 黑板擦 | hēi bǎn cā | Eraser |

Note: Two-digit numbers used in the current study are as follows: 15, 16, 17, 18, 19, 21, 23, 25, 26, 27, 28, 29, 33, 34, 36, 37, 38, 39, 42, 43, 45, 46, 47, 48, 49, 52, 53, 54, 56, 57, 58, 59, 62, 64, 65, 67, 68, 69, 71, 72, 73, 74, 75, 76, 78, 81, 82, 83, 84, 85, 86, 87, 91, 92, 93, 94, 95, 96.

## Appendix B. Supplementary data

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

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