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Neural Correlates of Quantity Processing of Numeral Classifiers

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Objective: Classifiers play an important role in describing the quantity information of objects. Few studies have been conducted to investigate the brain organization for quantity processing of classifiers. In the current study, we investigated whether activation of numeral classifiers was specific to the bilateral inferior parietal areas, which are believed to process numerical magnitude. ***Method:*** Using functional MRI, we explored the neural correlates of numeral classifiers, as compared with those of numbers, dot arrays, and nonquantity words (i.e., tool nouns). ***Results:*** Our results showed that numeral classifiers and tool nouns elicited greater activation in the left inferior frontal lobule and left middle temporal gyrus than did numbers and dot arrays, but numbers and dot arrays had greater activation in the middle frontal gyrus, precuneus, and the superior and inferior parietal lobule in the right hemisphere. No differences were found between numeral classifiers and tool nouns. ***Conclusion:*** The results suggest that quantity processing of numeral classifiers is independent of that of numbers and dot arrays, supporting the notation-dependent hypothesis of quantity processing.

Keywords: numerical processing, functional MRI, intraparietal sulcus, numeral classifiers

Numerous neuropsychological and neuroimaging studies have confirmed that the bilateral inferior parietal lobule, especially the brain area around the intraparietal sulcus (IPS), is crucial for numerical quantity processing (see reviews by Cantlon, Platt, & Brannon, 2009; Cohen Kadosh, Lammertyn, & Izard, 2008; Dehaene, Piazza, Pinel, & Cohen, 2003; Nieder & Dehaene, 2009). First, the IPS shows stronger activation induced by numerical processing than nonnumerical processing (e.g., Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Thioux, Pesenti, Costes, De Volder, & Seron, 2005). Second, the IPS is sensitive to both symbolic and nonsymbolic numerical magnitude (e.g., Dehaene et al., 2003; Hubbard et al., 2008; Nieder & Dehaene, 2009; Venkatraman, Ansari, & Chee, 2005). Third, the IPS is activated by quantity processing regardless of input–output channels (see reviews by Butterworth, 2010; Nieder & Dehaene, 2009).

Although most of the studies on the processing of quantity information have typically focused on numerical processing (symbolic or nonsymbolic processing), some studies have investigated the neural correlates of quantity processing in natural languages. For example, quantifiers have attracted some attention from researchers (e.g., Cappelletti, Butterworth, & Kopelman, 2006; Cipolotti, Butterworth, & Denes, 1991; McMillan, Clark, Moore, Devita, & Grossman, 2005; McMillan, Clark, Moore, & Grossman, 2006; Morgan et al., 2011; Polk, Reed, Keenan, Hogarth, & Anderson, 2001; Troiani, Clark, & Grossman, 2011; Troiani, Peelle, Clark, & Grossman, 2009; Wei, Chen, Yang, Zhang, & Zhou, 2012). Quantifiers are carriers of quantity information in natural languages, and their meanings depend on "mapping a truth-value to a set of objects or to a quantity of a mass substance" (Morgan et al., 2011, p. 3532). There are various types of qualifiers (see Appendix A for details of quantifiers that have been studied in brain imaging and neuropsychological research).

Thus far, results of the studies on the neural basis of quantifier processing have been inconsistent. Some studies have shown that quantity processing of quantifiers shared a neural basis similar to that of numbers. Both of them appear to be supported by the bilateral IPS. Researchers have reasoned that the comprehension of quantifiers requires a numerosity device (e.g., McMillan et al., 2005, 2006; Morgan et al., 2011; Troiani et al., 2009, 2011) and knowledge about numbers (McMillan et al., 2006) and therefore should activate the parietal cortex. Consistent with that argument, Polk et al. (2001) reported that their patient who had lesions in the left parietal lobe was

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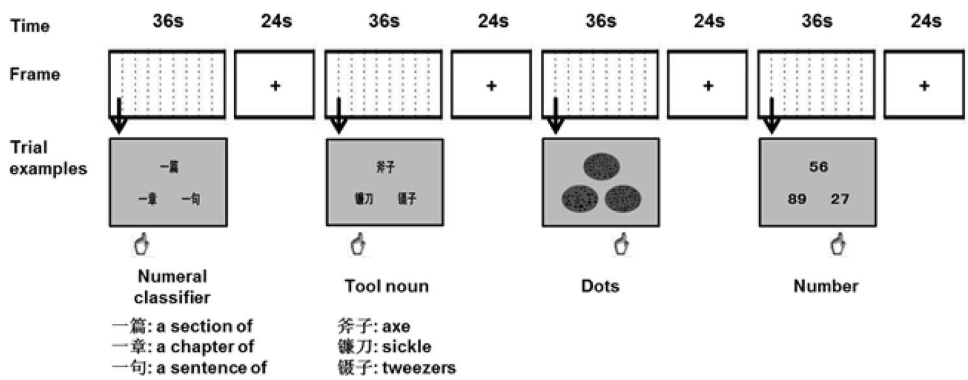

Figure 1. The experimental procedure of a run and sample trials in this study. Each run lasted 8 min and contained eight experimental blocks, two blocks for each type of materials. The blocks were pseudorandomized. Each block lasted 36 s with nine trials and was followed by 24-s rest.

deprived of abilities to process symbolic numbers and numerosity-related words (e.g., dozen, half, pair, single, and quarter), but possessed semantic knowledge about other kinds of words. Another report showed that a patient with semantic dementia preserved the ability of quantifier processing (e.g., several apples, a lot of cars) and nonverbal number processing, but showed impaired nonquantity processing (e.g., the girl with blond hair), suggesting that quantifiers and numbers share the same semantic system as numerical concepts (Cappelletti et al., 2006). A study of corticobasal syndrome patients and posterior cortical atrophy patients found that their impairment in processing cardinal quantifiers (e.g., "at least three"; see Appendix A for definitions of the types of quantifiers and additional examples) was partly due to a deficit in quantity knowledge related to temporal–parietal atrophy (Morgan et al., 2011). Finally, a neuroimaging study also showed that both first-order (e.g., "at least three") and higher order quantifiers (e.g., "less than half") activated the right inferior parietal cortex (McMillan et al., 2005).

Several studies further explored different types of quantifiers in detail, and found that the different types of quantifiers showed distinct neural bases involving a large-scale neural network including the parietal, frontal, and temporal cortices (e.g., McMillan et al., 2006; Morgan et al., 2011; Troiani et al., 2009, 2011). McMillan et al. (2006) suggested that first-order quantifiers (e.g., "all," "some," and "at least three") involve number knowledge such as the numeric property of a set and associated brain regions such as the IPS, whereas higher order quantifiers (e.g., "less than half," "odd number of," and "even number of") involve comparative judgment (and hence working memory and associated brain regions) as well as number knowledge. Similarly, Morgan et al. (2011) argued that an impairment in the processing of cardinal quantifiers (e.g., "at least three") is partly due to a deficit in quantity knowledge related to temporal–parietal atrophy, whereas the impairment in the processing of logical quantifiers (e.g., "some") and majority quantifiers (e.g., "at least half") is associated with the ability of perceptual logic comprehension or executive functions subserved by the frontal cortex. Finally, Troiani et al. (2009) also showed that cardinal quantifiers (e.g., "at least three," "more than two," "even," and "odd") require magnitude processing, which depends on a lateral parietal–dorsolateral prefrontal network, and logical quantifiers (e.g., "all" and "some") require perceptual logic processing, which depend on a rostral medial prefrontal–posterior cingulate network.

However, other studies found a dissociation in neural bases between quantifiers and numbers. Wei et al. (2012) reported that nonnumerical quantifiers (e.g., logical quantifiers, such as "some" and "none") depend on the temporal and frontal cortex, but not the IPS, suggesting that the neural basis of quantifier processing (at least nonnumerical quantifiers) may be similar to that for general semantic processing, rather than that for numerical processing. Similarly, another type of quantifiers—the classifiers, a linguistic device used to express quantity information of measurement units of objects in natural languages (Her & Hsieh, 2010; Hwang, Yoon, & Kwon, 2008)—has been found not to rely on the IPS. In their study of a Gerstmann's syndrome patient with hypodensity in the left frontoparietal region, Cipolotti et al. (1991) found that the patient had severe impairment for number processing but was able to perform the task of deciding which of two

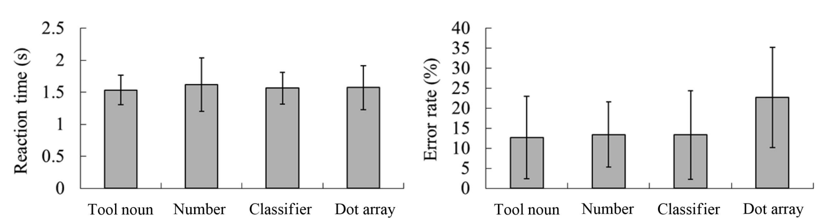

Figure 2. Average reaction times and error rates for all conditions.

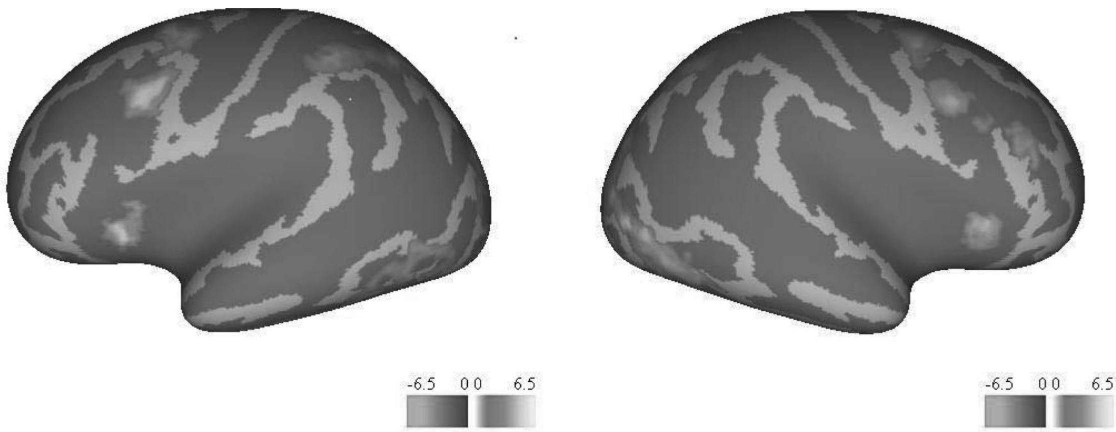

Figure 3. Brain regions commonly activated by numeral classifiers, tool nouns, numbers, and dot arrays. Height threshold: $p < .01$, uncorrected. Extent threshold: $k = 50$ voxels. Voxel size: $3 \times 3 \times 3$ mm^3.

classifiers (e.g., gram or kilo, meter or centimeter) expressed greater quantity. Therefore, it seems that classifier processing does not depend on number processing.

The current experiment is the first functional MRI (fMRI) study focusing on numeral classifiers. It aimed to investigate the neural correlates of numeral classifiers among healthy subjects. As Appendix A shows, numeral classifiers are a type of quantifiers with explicit quantity information that "must occur with a number and/or a demonstrative, or certain quantifiers before a noun" (C. Li & Thompson, 1981, p. 104). In Chinese language, numeral classifiers are syntactically obligatory in counting the quantity of head nouns, in which the numerals denote the numerical concepts of a set of objects, especially the cardinality of the set, and the classifiers describe the quantity properties or imputed characteristic of the objects as measuring units (P. Li, Barner, & Huang, 2008; Zhang, 2007).

Table 1
Common Activations in Brains for Numeral Classifiers, Tool Nouns, Numbers, and Dot Arrays, Relative to Rest

			Coordinate				
Hemisphere	Brain region	Brain activity	*X*	*Y*	*Z*	Volume	T
Right	Supplementary motor area	32	9	18	48	386	7.41
			−6	15	51		6.22
			−3	0	66		3.97
Left	Cerebellum	18	−6	−75	−24	2,976	6.99
			−24	−63	48		6.4
			−6	−81	−30		6.18
Right	Precentral gyrus	44	45	9	33	238	4.84
			39	−3	48		4.57
			45	0	60		4.14
Left	Lenticular nucleus, putamen	6	−30	−3	60	279	5.54
			−45	3	33		5.23
			−27	−6	51		4.67
Left	Insula	47	−33	21	−3	112	5.51
			−30	24	6		4.75
			−39	12	9		3.76
Right	Angular gyrus	7	30	−63	45	89	5.49
			−21	−3	15		4.84
Left	Lenticular nucleus, putamen	48	−21	9	3	167	4.55
			−9	−18	3		3.62
Right	Inferior frontal gyrus, triangular part	47	36	30	3	77	4.6
Right	Inferior frontal gyrus, triangular part	45	51	33	21	59	4.43
			42	36	15		3.8
			54	36	30		3.23
Right	Lenticular nucleus, putamen	48	21	−6	18	101	3.78
			21	3	15		3.4
			27	9	9		3.31

Note. Clusters that survived $p < .01$ (uncorrected) with spatial extent $k > 50$ voxels were considered statistically significant.

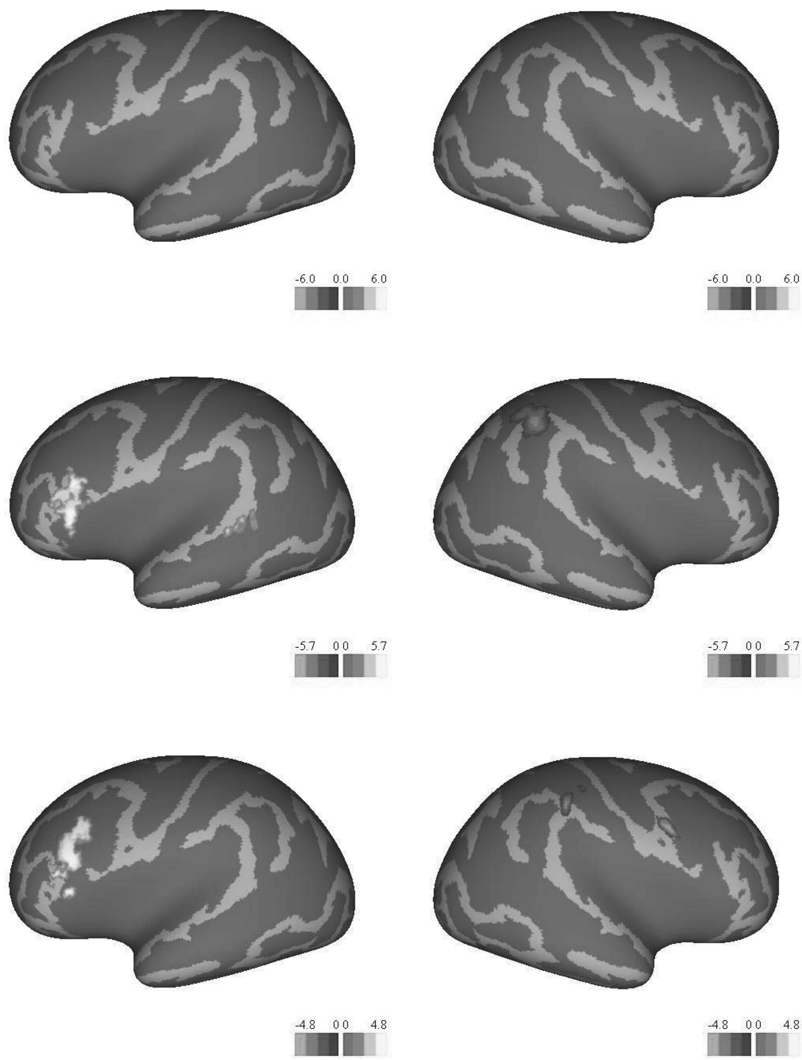

Figure 4. The contrasts of numeral classifiers with tool nouns, numbers, and dot arrays. Height threshold: $p <$ .001, uncorrected. Extent threshold: $k = 10$ voxels. Voxel size: $3 \times 3 \times 3$ mm^3. There were no differences between classifiers and tool nouns (upper panel). There were activation differences between classifiers and numbers (middle panel) and between classifiers and dot arrays (bottom panel). Greater activation for classifiers was typically in the left inferior frontal gyrus and left middle temporal gyrus (light gray), and greater activation for numbers or dot arrays was typically in the right inferior parietal lobule (dark gray).

In this study, numeral classifiers were compared with numbers, dot arrays, and nonquantity words (i.e., tool nouns). Based on previous results on numeral classifiers and quantifiers (e.g., Cipolotti et al., 1991; Wei et al., 2012), we hypothesized that numeral classifiers would not activate functional regions specialized for quantity processing of numbers (i.e., the IPS), but rather would activate the same regions as those for tool nouns. The latter was based on the close relations between numeral quantifiers and nouns: The classifiers would limit the types of head nouns presented after them by determining properties (e.g., animacy, function, size, shape, and consistence) associated with objects denoted by the head nouns (e.g., P. Li et al., 2008; Zhang, 2007). If our hypothesis was confirmed, our results would suggest that quantity processing depends on type of symbols representing quantities—the notation-dependent hypothesis of quantity processing (e.g., Campbell & Clark, 1988; Eger et al., 2003).

Method

Participants

Eighteen native Mandarin speakers were recruited from Beijing Normal University (BNU; nine women, mean age = 22.4 years, *SD* = 2.56). All participants were right-handed based on the Edinburgh Handedness Inventory (Oldfield, 1971). They had normal or corrected-to-normal visual acuity and no history of psychiatric or neurological disorders. They completed a screening form required by the BNU Imaging Center for Brain Research to ensure image quality and participants' safety. In-

Table 2
Effect Size for Contrast Analysis Between Numeral Classifiers and Other Three Conditions (Tool Nouns, Numbers, and Dot Arrays) in Each Region

Hemisphere	Brain region	Brain activity	Coordinate X	Coordinate Y	Coordinate Z	Volume	T
I. Greater activations for classifiers than for tool nouns							
None							
II. Greater activations for tool nouns than for classifiers							
None							
III. Greater activations for classifiers than for numbers							
Left	Inferior frontal gyrus, triangular part	45	−51	24	0	120	5.75
			−54	21	18		5.14
			−45	30	6		4.45
Left	Inferior frontal gyrus, opercular part	47	−39	33	−12	11	4.35
Left	Middle temporal gyrus	21	−60	−36	0	15	3.68
			−54	−48	0		3.46
			−60	−45	6		3.39
IV. Greater activations for numbers than for classifiers							
Right	Precuneus	7	6	−75	51	200	6.21
Right	Superior parietal lobule	7	18	−72	57		5.2
Left	Precuneus	7	−6	−63	48		4.28
Right	Inferior parietal lobule	40	42	−48	48	84	5.08
			39	−42	39		4.31
Right	Angular gyrus	40	33	−54	42		3.86
Right	Superior frontal gyrus	8	27	15	60	87	4.97
Right	Middle frontal gyrus	8	24	15	51		4.57
Right	Cerebellum 8	37	36	−48	−42	11	4.11
V. Greater activations for classifiers than for dot arrays							
Left	Inferior frontal gyrus, triangular part	48	−45	15	30	161	4.92
			−42	24	24		4.72
			−51	21	21		4.69
VI. Greater activations for dot arrays than for classifiers							
Left	Superior occipital gyrus	18	−12	−102	15	15	4.8
Right	Lingual gyrus	18	18	−84	−12	21	4.7
Right	Medial cingulate and paracingulate gyri	32	6	33	33	14	4.47
Right	Fusiform gyrus	19	30	−69	−9	23	4.43
Left	Putamen	11	−18	21	−3	13	4.26
			−24	18	−9		3.34
Right	Superior frontal gyrus	46	24	45	21	25	4.18
			21	54	21		3.93
Right	Anterior cingulate and paracingulate gyri	32	15	48	21		3.45
Right	Anterior cingulate and paracingulate gyri	32	6	45	21	11	4.14
			9	39	15		3.81
Right	Inferior parietal lobule	2	51	−33	51	10	4
Left	Middle frontal gyrus	9	−24	48	33	17	4
			−15	51	39		3.79
Left	Medial cingulate and paracingulate gyri	23	−3	−24	45	11	3.96
Right	Precentral gyrus	6	54	6	27	12	3.93
Left	Anterior cingulate and paracingulate gyri	32	−3	42	21	11	3.92
Left	Calcarine fissure and surrounding cortex	17	6	−93	−3	11	3.89
			6	−99	3		3.58
Right	Superior frontal gyrus, medial	10	3	57	6	12	3.74
Left	Calcarine fissure and surrounding cortex	17	−9	−102	0	17	3.68
			−12	−93	−6		3.52

Note. Region clusters that survived $p < .001$ (uncorrected) with spatial extent $k > 10$ voxels were considered statistically significant.

formed consents were obtained following the protocol approved by the Institutional Review Board of the BNU Imaging Center.

Stimuli and Materials

There were four experimental conditions: numeral classifiers, tool nouns, numbers, and dot arrays. Fifty-eight numeral classifiers and 58 tool nouns were used (see Appendix B). These numeral classifier phrases included only a numeral (the number "one") and a classifier to reduce influence of other types of words. The numeral (the number "one") ensured that the participants would treat these phrases as classifiers rather than their alternative meanings. For the number condition, 59 two-digit numbers were chosen within the range from 10 to 99; for the dot condition, 59 dot arrays had quantities that also ranged from 10 to 99. The number or word stimuli were 30 mm in height and 15 mm in width, and the size of the box for the dot arrays was 60 mm in height and 60 mm in width.

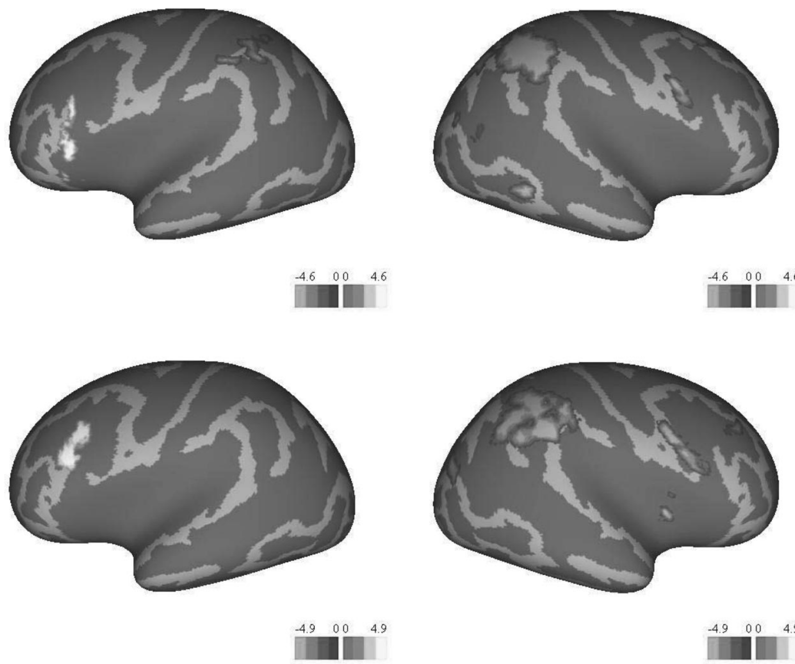

Figure 5. The contrasts of tool nouns and other conditions. Height threshold: $p < .001$, uncorrected. Extent threshold: $k = 10$ voxels. Voxel size: $3 \times 3 \times 3$ mm^3. There were activation differences between tool nouns and numbers (upper panel) and between tool nouns and dot arrays (bottom panel). Greater activation for tool nouns was typically in the left inferior frontal gyrus (light gray), and greater activation for numbers or dot arrays was typically in the right superior and inferior parietal lobules (dark gray).

Procedure

We used a block design for the semantic distance comparison task because such a design has been found to have superior statistical power (Friston, Zarahn, Josephs, Henson, & Dale, 1999). There were two 8-min runs. In total, 144 trials were divided equally into 16 blocks, eight for each of the two runs. Each block lasted 36 s, and was followed by a 24-s rest, with no repeated targets in the same block (see Figure 1). During the experiment, the order of the blocks was pseudorandomized, and the trial order was randomized within each block for each paorticipant. The order of the blocks was counterbalanced by dividing the 18 participants into two groups, each with a different order of the blocks. Before scanning, participants completed a practice block consisting of nine trials.

In each trial of the task blocks, the stimulus was presented in the center of the screen for up to 3,500 ms, and participants were asked to give a response as quickly as possible. Once participants responded, the stimulus disappeared, followed by a blank interval to complement the remaining time; 500 ms later, the next trial appeared. Each task block was followed by a rest block of 24 s, during which participants were asked to view a fixation cross. The stimuli were presented via back-projection onto a semilucent screen and then reflected to a mirror attached to the head coil. Exposure and timing of stimuli were controlled by Eprime software.

A semantic distance comparison task was used for all four types of stimuli (numeral classifiers, numbers, dot arrays, and tool nouns). A target item was presented in the top part of the screen and two alternative items at the bottom horizontally. Participants were instructed to judge which of the two items at the bottom had a closer semantic relation with the target. Participants pressed a key with the hand corresponding to the position of the answer.

fMRI Data Acquisition

MRI scans were collected on a Siemens (Munich, Germany) 3T Trio scanner using a standard eight-channel head coil (Beijing Normal University, China). Functional volumes were acquired using a T2*-weighted gradient echo-planar imaging sequence (32 axial slices, thickness, 4 mm; field of view, 200 mm; matrix size, 64×64; repetition time, 2,000 ms; echo time, 30 ms; flip angle, 90°).

Statistical Analysis of the fMRI Data

The preprocessing stage, including realignment, normalization, and smoothing, was performed using SPM 5 (http://www.fil.ion.ucl.ac.uk/spm/software/spm5/). All volumes were realigned to the first volume and spatially normalized to a common value to correct for whole brain differences over time. Data were normalized to a standard template in the Montreal Neurological Institute space for spin history and then smoothed with an isotropic 4-mm full-width-half-maximum Gaussian kernel and high-pass filter at a cutoff of 128 s. The images of the 18 participants were entered into a two-step statistical analysis to examine the activation patterns elicited by numeral classifiers in contrast to the other three types of stimuli.

Table 3
Effect Size for Contrast Analysis Between Tool Nouns and Other Conditions (Numbers and Dot Arrays) in Each Region

Hemisphere	Brain region	Brain activity	Coordinate			Volume	T
			X	*Y*	*Z*		
I. Greater activations for tool nouns than for numbers							
Left	Inferior frontal gyrus, orbital part	47	−27	30	−9	19	4.69
Left	Inferior frontal gyrus, orbital part	47	−39	33	−12	10	4.69
Left	Inferior frontal gyrus, triangular part	47	−48	24	0	28	4.66
Left	Inferior frontal gyrus, triangular part	48	−51	21	24	20	3.82
Left	Inferior frontal gyrus, opercular part	48	−51	18	15		3.65
Left	Inferior frontal gyrus, triangular part	45	−54	27	18		3.54
II. Greater activations for numbers than for tool nouns							
Right	Inferior parietal lobule	40	42	−48	45	647	7.02
Right	Precuneus	7	6	−75	51		6.5
Right	Superior parietal lobule	7	18	−72	57		6.3
Right	Middle frontal gyrus	8	27	18	57	117	5.51
Right	Superior frontal gyrus	6	30	3	66		4.03
Right	Inferior parietal gyrus	40	−39	−42	42	39	4.74
			−36	−48	48		4.21
			−48	−48	48		4.08
Left	Superior frontal gyrus	6	−15	12	60	16	4.61
Left	Middle frontal gyrus	6	−24	6	60		3.25
Right	Inferior temporal gyrus	20	54	−48	−12	17	4.44
Left	Precuneus	7	−6	−63	48	50	4.2
			−12	−75	48		4.07
			−6	−69	57		3.65
Left	Inferior parietal lobule	40	−54	−39	51	14	4.19
Right	Inferior frontal gyrus, orbital part	44	54	9	24	24	4.15
Right	Middle occipital gyrus	39	39	−75	21	10	3.58
			39	−69	15		3.53
III. Greater activations for tool nouns than for dot arrays							
Left	Inferior frontal gyrus, opercular part	44	−45	15	33	106	5.02
Left	Inferior frontal gyrus, triangular part	48	−51	21	24		4.97
			−42	24	21		4.67
IV. Greater activations for dot arrays than for tool nouns							
Right	Insula	48	39	0	6	13	5.23
Right	Inferior parietal lobule	40	42	−48	48	277	5.15
			54	−48	42		5.07
			51	−33	51		4.77
Right	Middle occipital gyrus	19	36	−84	24	22	4.68
Right	Inferior frontal gyrus, opercular part	44	54	9	24	57	4.66
			57	15	15		4.35
Right	Superior parietal lobule	7	15	−72	57	98	4.57
Right	Superior occipital gyrus	7	27	−69	39		4.38
Right	Superior parietal lobule	7	21	−72	51		4.31
Right	Middle frontal gyrus	45	45	30	39	13	4.21
Right	Fusiform gyrus	19	30	−69	−6	10	4.11
Right	Medial cingulate and paracingulate gyri	32	6	36	33	10	4.03
Right	Medial cingulate and paracingulate gyri	23	3	−36	45	35	3.99
Right	Precuneus		3	−48	45		3.85
Left	Medial cingulate and paracingulate gyri		0	−21	42		3.62

Note. Region clusters that survived $p < .001$ (uncorrected) with spatial extent $k > 10$ voxels were considered statistically significant.

Results

Figure 2 shows the mean reaction time (RT) and error rates. RTs and error rates were analyzed with a repeated measures analysis of variance (four types of materials: numeral classifiers, tool nouns, numbers, and dot arrays). The main effect of type of materials was significant in error rates, $F(1, 18) = 3.64$, $p < .05$, but not in RT. Further simple effects tests showed that error rates were higher for dot arrays than for numeral classifiers, $p < .01$, and tool nouns and numbers, $p < .001$.

Figure 3 and Table 1 present the brain activities for numeral classifiers and the other types of materials (tool nouns, numbers, and dot arrays) relative to rest according to a conjunction analysis. Generally, the four conditions commonly activated the right inferior frontal gyrus, right angular gyrus, right supplementary motor area, right precentral gyrus, left insula, left cerebellum, and bilateral lenticular nucleus.

The contrast analysis between numeral classifiers and tool nouns showed no areas with significant activations, suggesting that these two types of materials had similar neural basis. The effect size for each condition in each region is shown in Figure 4, upper panel, and Table 2 ($p < .001$, uncorrected, and spatial extent $k > 10$ voxels). Even with a more lenient threshold ($p < .01$, uncorrected, and spatial extent $k > 10$ voxels), the results did not change.

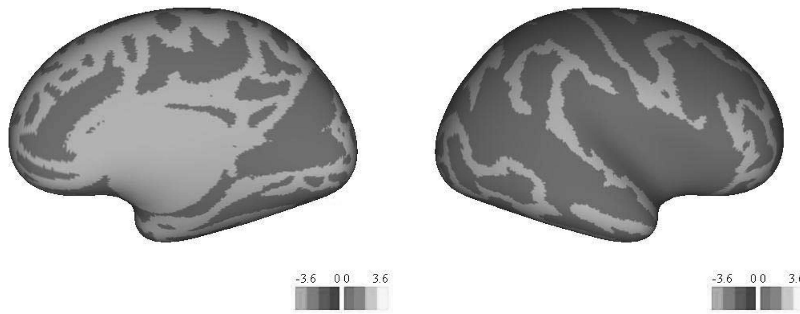

Figure 6. The contrasts of numbers and dot arrays. Height threshold: $p < .001$, uncorrected. Extent threshold: $k = 10$ voxels. Voxel size: $3 \times 3 \times 3$ mm^3. There were no greater activation for numbers than dot arrays, and the only area with greater activation for dot arrays than numbers was in the right fusiform gyrus (dark gray).

The comparison between numeral classifiers and numbers revealed that numeral classifiers had greater activation in the inferior frontal gyrus and middle temporal gyrus in the left hemisphere, but numbers induced more activation in the precuneus in the left hemisphere, and the superior and middle frontal gyrus, superior and inferior parietal lobule, precuneus, angular gyrus, and cerebellum in the right hemisphere. The effect size for each condition in each region is plotted in Figure 4, middle panel, and Table 2.

The comparison between numeral classifiers and dot arrays found that numeral classifiers elicited higher activation in the inferior frontal gyrus in the left hemisphere. Dot arrays elicited more activation in the middle frontal gyrus, cingulate gyri, superior occipital gyrus, putamen, and calcarine fissure in the left hemisphere, and the cingulate gyri, lingual gyrus, fusiform gyrus, inferior parietal lobule, superior frontal gyrus, and precentral gyrus in the right hemisphere (see Figure 4, bottom panel, and Table 2).

The contrast analysis between tool nouns and numbers showed that tool nouns had stronger effects only in the left inferior frontal gyrus; numbers elicited stronger activation in the superior and middle frontal gyrus, inferior parietal lobule, and precuneus in the left hemisphere, and the superior and inferior parietal lobule, superior and middle frontal gyrus, orbital part of inferior frontal gyrus, inferior temporal gyrus, middle occipital gyrus, and precuneus in the right hemisphere (see Figure 5, upper panel, and Table 3).

The contrast analysis between tool nouns and dot arrays showed that tool nouns elicited more activation in the left inferior frontal gyrus; dot arrays induced more activation in the cingulate gyri in the left hemisphere, and the superior and inferior parietal lobule, middle frontal gyrus, orbital part of inferior frontal gyrus, superior and middle occipital gyrus, fusiform gyrus, cingulate gyri, precuneus, and insula in the right hemisphere (see Figure 5, bottom panel, and Table 3).

The contrast analysis between numbers and dot arrays found that numbers did not elicit significantly more activation than dot arrays, and dot arrays had stronger activation only in the right fusiform gyrus (see Figure 6).

Discussion

We used fMRI to investigate the neural basis of processing numeral classifiers, and found that all four types of stimuli (numeral classifiers, numbers, tool nouns, and dot arrays) activated the inferior frontal gyrus, angular gyrus, supplementary motor area, and precentral gyrus in the right hemisphere, the insula and cerebellum in the left hemisphere, and bilateral lenticular nucleus. Contrast analyses showed that classifiers had similar activation with tool nouns, which was distinct from activations elicited by numbers and dot arrays. Classifiers induced more activation in the left frontal and temporal areas, and numbers showed stronger activation in the left precuneus and the right frontal and parietal areas. These findings suggest that unlike numbers or dot arrays, numeral classifiers do not rely on the IPS. In other words, the IPS does not seem to be a brain region for all abstract quantity processing. This notion is consistent with the growing literature that semantic processing is supported by distributed networks (e.g., see reviews by Cappa, 2012; Price, 2012).

First, our results that numbers and numerosities activated the parietal cortex are consistent with previous studies (see a meta-analysis by Arsalidou & Taylor, 2011; reviews by Cantlon et al., 2009; Cohen Kadosh et al., 2008; Nieder & Dehaene, 2009). The bilateral inferior parietal area is considered an important region for quantity processing and is independent of input–output channels and tasks (e.g., Chochon, Cohen, van de Moortele, & Dehaene, 1999). In addition, we also found that numbers and dot arrays had greater activation in the prefrontal cortex than did numeral classifiers and tool nouns. This was probably due to the involvement of visuospatial working memory in number and numerosity processing (e.g., Holloway, Price, & Ansari, 2010, for Arabic numbers and squares; Jacob & Nieder, 2009, for fractions).

Second, the brain regions that were activated more strongly by classifiers and tool nouns than by numbers and dot arrays were the classical areas for general semantic and verbal processing, especially in the left hemisphere (Booth et al., 2006). For example, in an early PET study of word processing, Martin, Wiggs, Ungerleider, and Haxby (1996) found that passive viewing of tool nouns induced activation in the left inferior frontal gyrus and middle temporal gyrus. Later research has confirmed the role of the left inferior frontal gyrus and left fusiform gyrus in the processing of words in different languages, including Korean (e.g., Yoon, Chung, Kim, Song, & Park, 2006) and Chinese (e.g., Xue, Dong, Jin, & Chen, 2004). Therefore, the quantity information in classifiers seems to be processed in the same brain regions as general semantic processing.

Our results add to a small but growing literature on the neural basis of quantifier processing. They are consistent with at least two previous studies. In a patient study, Cipolotti et al. (1991) found that the patient had impaired number processing but intact classifier processing. Wei et al. (2012) showed that quantifier processing did not rely on the IPS, but rather on the temporal and frontal cortices. Taken together, from the results of these studies as well as those of the current study, it appears that the processing of quantifiers, including classifiers, shares a common neural basis with language processing but not with number processing. These results also support the hypothesis that quantity processing is notation-dependent, not notation-independent (e.g., Dehaene, 1992). The notation-dependent hypothesis was proposed by Campbell based on results from a number of behavioral studies that showed how the presentation format (Arabic digits vs. English number words) influenced number processing such as estimation of numerical magnitude (Campbell, 1994; Campbell & Clark, 1988). It has been confirmed by a series of cognitive neuroscience experiments, which found that different types of numerical symbols induce different activation in the bilateral IPS (e.g., Ansari, 2007; Cohen Kadosh, Muggleton, Silvanto, & Walsh, 2010; Diester & Nieder, 2007; Holloway et al., 2010; Jacob & Nieder, 2009; Santens, Roggeman, Fias, & Verguts, 2010).

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Appendix A

Types of Quantifiers Used in Previous Neuroimaging and Neuropsychological Studies of Numerical Processing

Type of quantifier (and relevant studies)	Definition (sources)	Example	Cognitive mechanism involved and relations to other subtypes
First-order quantifier (McMillan et al., 2005, 2006)	A word or phrase containing a determiner, functionally pointing from sets to numbers and truth values (see Keenan & Stavi, 1986; McMillan et al., 2005).	"all," "some," and "at least three"	It depends on number knowledge to determine the numeric property of a set.
Higher order quantifier (McMillan et al., 2005, 2006)	A phrase containing a determiner that includes comparisons among sets (see Keenan & Stavi, 1986; McMillan et al., 2005).	"less than half," "odd number of," and "even number of"	In addition to number knowledge, the higher order quantifier depends on working memory to make comparative judgments.
Cardinal quantifier (or numerical quantifier; Morgan et al., 2011; Troiani et al., 2009)	A phrase mapping numbers to the quantity of a set of objects.	"at least three," "more than two," "even," and "odd"	It depends partly on knowledge system of magnitude and numbers. It is partly overlapped with the first-order and higher order ones.
Logical quantifier (or Aristotelean quantifier; Morgan et al., 2011; Troiani et al., 2009)	A word or phrase mapping properties to truth values (Keenan & Paperno, 2010).	"all" and "some"	It is a subset of first-order quantifiers that involve truth values, and also needs an elementary logic system to judge the presence or absence of a unique target.
Majority quantifier (Morgan et al., 2011)	A phrase determining the cardinality of subsets of objects (Morgan et al., 2011).	"at least half"	It is a subset of high-order quantifiers that relies on both quantity knowledge and executive resources such as working memory.
Classifier (or measure word; Cipolotti et al., 1991; X. Li & Bisang, 2012)	A type of quantifiers with explicit quantity information that "must occur with a number and/or a demonstrative, or certain quantifiers before a noun" (C. Li & Thompson, 1981, p. 104) and as measuring units of individual persons, objects, and things (P. Li et al., 2008).	"gram," "kilo," "meter," "centimeter," "a piece of," "two sheets of," "a cup of," "a drop of," "two bottles of," "a pair of," "a heap of," and "a bunch of"	Like other types of quantifiers, classifiers have quantity information, which is used to determine the quantity or numerosity of the head nouns (e.g., Clark & Grossman, 2007; Her, 2012).

(*Appendices continue*)

Appendix B

Numeral Classifiers, Tool Nouns, Numbers, and Dot Arrays Used in the Current Study

Chinese name	Pronunciation	English[a]	Chinese name	Pronunciation	English
		1. Numeral Classifiers			
一幢	yī zhuàng	unit for house or building	一栋	yī dòng	unit for horse or building
一间	yī jian	unit for room	一名	yī míng	unit for person
一位	yī wèi	unit for person	一群	yī qún	a group of
一桶	yī tǒng	pailful	一套	yī tào	a suite of
一滴	yī dī	a drop of	一袋	yī dài	pocketful
一兜	yī dôu	a bag of	一粒	yī lì	a grain of
一篇	yī piān	a section of or unit of article/paper	一章	yī zhāng	a chapter of
一句	yī jù	a sentence of	一摞	yī luó	a pile of
一沓	yī tà	a pile of	一页	yī yè	a page of
一根	yī gçn	a stick of	一条	yī tiáo	an item of
一堆	yī duī	a heap of	一张	yī zhāng	a sheet of
一层	yī céng	a layer of	一支	yī zhī	a piece of
一杆	yī gǎn	a pole of	一捆	yī kǔn	a bundle of
一本	yī běn	a copy of	一家	yī jiā	a family
一户	yī hù	a family of	一卷	yī juàn	a reel
一件	yī jiàn	a piece of	一顶	yī ding	unit for hat
一双	yī shuāng	a pair of	一副	yī fù	a pair of
一打	yī dá	a dozen	一束	yī shù	a bunch of
一捧	yī pěng	in both hands of	一簇	yī cù	tuft
一株	yī zhū	unit for plant	一行	yī háng	a row of
一届	yī jiè	term	一级	yī jí	a grade of
一班	yī ban	troupe	一瓶	yī ping	jarful
一杯	yī bçi	a cup of	一缸	yī gang	an urn of
一勺	yī sháo	spoonful	一匙	yī chí	spoonful
一锅	yī guô	potful	一尾	yī wěi	unit for fish
一节	yī jié	a lesson	一段	yī duàn	a paragraph of
一盆	yī pén	a basin of	一朵	yī duǒ	unit for flower
一串	yī chuàn	a string of	一颗	yī kç	a piece of
一缕	yī l[caron]ü	a stream of	一册	yī cè	a copy of
		2. Tool Nouns			
尺子	chǐ zi	ruler	橡皮	xiàng pí	eraser
锯子	jù zi	saw	钢笔	gāng bǐ	pen
铅笔	qiān bǐ	pencil	粉笔	fěn bǐ	chalk
圆规	yuán guī	compasses	订书机	dīng shū jī	stapler
小刀	xiǎo dāo	knife	围棋	wéi qí	Go (game)
骰子	shǎi zi	dice	麻将	má jiàng	mahjong
象棋	xiàng qí	Chinese chess	竖笛	shù dí	clarinet
喇叭	lǎ bā	trumpet	大鼓	dà gǔ	bass drum
口琴	kǒu qín	harmonica	小号	xiǎo hào	trumpet
二胡	èr hú	urheen	笛子	dí zi	flute
古筝	gǔ zhçng	a 21-or 25-stringed plucked instrument	箫	Xiāo	a vertical bamboo flute
天平	tiān píng	scale	砝码	fǎ mǎ	weight
蜡烛	là zhú	candle	台灯	tái dçng	desk lamp
榔头	láng tóu	hammer	锤子	chuí zi	hammer
钳子	qián zi	pliers	斧子	fǔ zi	axe
镊子	niè zi	tweezers	螺丝刀	luó sī dāo	screwdriver
扳手	bān shǒu	wrench	眉笔	méi bǐ	eyebrow pencil
耙子	pá zi	rake	铲子	chǎn zi	shovel
电锯	diàn jù	electric saw	拖把	tuô bǎ	mop
起子	qǐ zi	bottle opener	犁	lí	plough
剪刀	jiǎn dāo	scissors	电钻	diàn zuàn	electric drill
刷子	shuā zi	brush	镰刀	lián dāo	sickle
菜刀	cài dāo	kitchen knife	案板	àn bǎn	chopping board
筷子	kuài zi	chopsticks	锅铲	guō chǎn	spatula
杯子	bçi zi	cup	梳子	shū zi	comb
吹风机	chuī fçng jī	hair drier	电熨斗	diàn yùn dǒu	electric iron
勺子	sháo zi	ladle	牙刷	yá shuā	toothbrush
汤勺	tāng sháo	soup ladle	直尺	zhíchǐ	ruler
圆珠笔	yuán zhū bǐ	ball-point pen	裁纸刀	cháí zhǐ dāo	paper knife

Note. Two-digit numbers used in the current study are as follows: 11, 12, 13, 17, 18, 19, 21, 24, 25, 26, 27, 28, 29, 32, 33, 35, 36, 37, 38, 39, 41, 42, 43, 45, 46, 47, 48, 49, 51, 52, 53, 54, 56, 57, 58, 59, 62, 63, 64, 65, 67, 68, 69, 71, 72, 73, 74, 75, 76, 78, 81, 82, 83, 84, 86, 87, 91, 93, 94. Quantities of dot arrays used in the current study are as follows: 10, 13, 20, 23, 25, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 46, 47, 49, 50, 51, 52, 54, 55, 56, 57, 59, 60, 61, 62, 63, 66, 67, 68, 69, 70, 72, 73, 74, 75, 76, 77, 78, 80, 81, 82, 84, 85, 86, 88, 89, 90, 91, 92, 93, 94, 96, 97, 98, 99.

[a] All listed Chinese classifiers were different from one another, but some can be used interchangeably and thus have the same English translation.

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