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Dissociated Neural Correlates of Quantity Processing of Quantifiers, Numbers, and Numerosities

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Abstract: Quantities can be represented using either mathematical language (i.e., numbers) or natural language (i.e., quantifiers). Previous studies have shown that numerical processing elicits greater activation in the brain regions around the intraparietal sulcus (IPS) relative to other semantic processes. However, little research has been conducted to investigate whether the IPS is also critical for the semantic processing of quantifiers in natural language. In this study, 20 adults were scanned with functional magnetic resonance imaging while they performed semantic distance judgment involving six types of materials (i.e., frequency adverbs, quantity pronouns and nouns, animal names, Arabic digits, number words, and dot arrays). Conjunction analyses of brain activation showed that numbers and dot arrays elicited greater activation in the right IPS than did words (i.e., animal names) or quantifiers (i.e., frequency adverbs and quantity pronouns and nouns). Quantifiers elicited more activation in left middle temporal gyrus and inferior frontal gyrus than did numbers and dot arrays. No differences were found between quantifiers and animal names. These findings suggest that, although quantity processing for numbers and dot arrays typically relies on the right IPS region, quantity processing for quantifiers typically relies on brain regions for general semantic processing. Thus, the IPS does not appear to be the only brain region for quantity processing. *Hum Brain Mapp 35:444–454, 2014.* © 2012 Wiley-Periodicals, Inc.

Key words: numerical processing; intraparietal sulcus; numerosity; quantity processing; quantifier

INTRODUCTION

Numbers can be represented in different forms, such as Arabic numbers (e.g., 1, 2, and 3), dots (e.g., •, ••, and •••), number words (e.g., one, two, and three), Roman numerals (I, II, and III), and so on. Many studies have focused on the neural basis of numerical processing and have explored how the human brain processes various number forms [Ansari et al., 2006; Dehaene, 1996; Piazza et al., 2004; Pinel et al., 1999, 2001, 2004].

Several lines of neuropsychological and neuroimaging studies have shown that the intraparietal sulcus (IPS) plays an important role in the representation and manipulation of abstract numerical quantity or magnitude regardless of modality [visual or auditory; Cohen Kadosh et al.,

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2007; Dehaene et al., 1999, 2003, 2004; Eger et al., 2003; Kadosh et al., 2005; Piazza et al., 2007; Simon et al., 2002, see a review by Cohen Kadosh et al., 2008]. First, the numerical distance effect [Moyer and Landauer, 1967] in numerical comparison tasks (e.g., Which of the numbers 5 and 6 is bigger?) is localized to the IPS [Pinel et al., 2001]. For example, an early PET study found that activation in the IPS was greater for the number pairs with a smaller numerical distance (e.g., 5 vs. 6) than for the number pairs with a larger numerical distance [e.g., 2 vs. 9; Dehaene, 1996].

Second, the IPS shows greater activation during numerical processing relative to non-number processing. In a functional magnetic resonance imaging (fMRI) study with a target detecting paradigm, numbers produced greater activation than did colors and letters, regardless of the modality of stimuli [i.e., auditory and visual; Eger et al., 2003]. Research has demonstrated that semantic processing of numbers (e.g., Is six larger than five?) elicited greater activation in the IPS compared with processing of ferocity of animals [Thioux et al., 2005].

Third, researchers have found greater activation in the IPS when participants perform arithmetic processing with a greater demand on quantity processing (e.g., approximate calculation) than that with a greater demand on verbal processing [e.g., exact calculation; Dehaene et al., 1999; Lemer et al., 2003; Pica et al., 2004; Stanescu-Cosson et al., 2000]. Another study found that multiplication, which mainly relies on verbal codes, induced greater activation in the angular gyrus, whereas subtraction, which mainly relies on quantity processing, induced greater activation in the IPS [Lee, 2000].

Fourth, studies also found that the IPS is sensitive to both symbolic and nonsymbolic numerical magnitude [Cantlon et al., 2006; Dehaene et al., 2003; Piazza et al., 2004; Venkatraman et al., 2005]. Participants were shown sets of dots varying in shape and number and their bilateral IPS was found to respond only to changes in number, not those in shape [Piazza et al., 2004]. Similarly, researchers found that the bilateral IPS was activated by changing numbers rather than changing areas of squares [Ansari et al., 2006]. However, not all studies found the same results. For example, there were no significant adaptive activation changes in the parietal lobe when participants were performing a number comparison task [Shuman and Kanwisher, 2004]. Cohen Kadosh et al. [2011] also used the adaptation paradigm of fMRI and found that the format change (e.g., from dots to digits) elicited a greater adaptation effect than did the magnitude change in the same intraparietal region.

Number-specific processing has been used as evidence for the abstract quantity hypothesis about the IPS. This hypothesis, also known as the notation-independent hypothesis, posits that quantity processing is housed in the same IPS region regardless of its notations [Dehaene, 1996; Eger et al., 2003; Pinel et al., 2001; Venkatraman et al., 2005]. All previous evidence for this hypothesis has relied on quantity processing of numbers and numerosities. Quantities, however, can also be represented by natural language (i.e., quantifiers). For example, frequency adverbs (e.g., always, occasionally, and seldom) describe the number of times certain events take place. Linguists consider frequency adverbs as representing magnitude information [Bass et al., 1974; Schriesheim and Novelli, 1989; Schriesheim and Schriesheim, 1978]. Words other than adverbs (e.g., adjectives, pronouns, and nouns) also denote quantity. For example, quantifiers such as “some,” “many,” “plenty,” and “countless” pertain to “how many.” In fact, quantifier has been defined as a determiner or pronoun that expresses quantity information [Oxford Dictionary, 2000] and treated as a type of numerical concept without exact number [Cappelletti et al., 2006]. It is thus reasonable to conclude that quantifiers and numbers both contain quantity information, although the quantity expressed by quantifiers is not as exact as that expressed by numbers. We nevertheless rely on both of them to express quantity information in our daily life. Some primitive tribes that have not developed a mature number system (e.g., Arabic digits) can only use quantity words (e.g., some, many, not many, so many, and really many) to convey quantity information [Pica et al., 2004].

According to the notation-independent hypothesis, semantic processing of quantifiers should also be subserved by the same brain region that processes numbers and numerosities. Several neuropsychological and neuroimaging studies have been conducted to investigate the neural basis of processing quantifiers [Cappelletti et al., 2006; Cipolotti et al., 1991; McMillan et al., 2005, 2006; Morgan et al., 2011; Polk et al., 2001; Troiani et al., 2009, 2011]. Results from these neuropsychological studies have been inconsistent. Several neuropsychological studies showed that quantifier processing and numerical processing shared similar semantic magnitude systems in the brain. To illustrate, one report described a patient with lesions in the left parietal lobe who had impaired abilities to process symbolic numbers and number-related words (e.g., dozen, half, pair, single, and quarter). Notably, this patient showed normal processing of other semantic knowledge [Polk et al., 2001]. Similarly, a patient with semantic dementia was found to show impaired ability to process nonquantifier words (e.g., the girl with blond hair) but had a normal capacity to understand quantifier words (e.g., several apples, a lot of cars) and numerical knowledge [Cappelletti et al., 2006]. In contrast, corticobasal degeneration patients show impaired understanding of verbal quantifiers [e.g., McMillan et al., 2006; Morgan et al., 2011; Troiani et al., 2009, 2011] and numbers [e.g., Halpern et al., 2004; McMillan et al., 2006], but often have normal language abilities [e.g., Troiani et al., 2011]. Finally, one neuroimaging study of normal adults compared the neural bases of first-order versus higher order quantifiers. The first-order quantifiers identify a number state, such as “at least 3,” “at most 5,” “exactly 2,” and “between 4 and 6.” The higher order quantifiers involve comparisons of the relative size of sets, such as "less than half," "more than half," and "an even number of" [McMillan et al., 2005, 2006]. Both types of quantifiers activated the right inferior parietal cortex possibly due to its role in number processing, but the higher order quantifiers induced a higher degree of activation in the right dorsolateral prefrontal cortex perhaps due to the involvement of working memory [McMillan et al., 2005].

Other results suggest that quantifier processing could be dissociated from numerical processing, which seems to support the notation-dependent hypothesis (i.e., quantifiers use notations different from numbers and thus should involve different neural basis). For example, a Gerstmann's syndrome patient with severely impaired number processing could correctly decide which of two measurement terms denoted greater quantity. The terms included weight (e.g., gram, kilo, tonellata, and quintale) and length units [e.g., meter, centimeter, and kilometer; Cipolotti et al., 1991]. Although corticobasal degeneration patients relative to controls could not understand perfectly the cardinal quantifiers (e.g., "The blonde lady is holding more than three flowers"), but their processing of logical quantifiers (e.g., "There are some orange pumpkins in the red truck") was not impaired [Morgan et al., 2011]. Finally, Troiani et al. [2009] found that numerical quantifiers (e.g., "at least three," "more than two," and even vs. odd) activated the parietal lobe more than did logical quantifiers (e.g., some and all), which instead elicited greater activation in the cingulate gyrus.

To determine whether the processing of quantifiers would lead to a category-specific neural response in the parietal cortex, quantifiers should be directly compared against nonquantity words, which has not been done in previous neuroimaging studies. In this study with a sample of healthy Chinese adults, the brain activation elicited by both quantifiers and nonquantity words were directly compared. As a comparison task, participants also judged the ferocity of animals because a previous study found that greater activation in the IPS was elicited by numbers than by the ferocity of animals [Thioux et al., 2005].

In sum, this study tested two alternative hypotheses: the notation-independent hypothesis and the notation-dependent hypothesis. The notation-independent hypothesis would predict that semantic processing of quantifiers would elicit greater activation in the IPS region than would semantic processing of animal names because the processing of all types of quantity (including that conveyed by quantifiers) should be processed in the IPS. The notation-dependent hypothesis of quantity processing would predict that semantic processing of quantifiers and animal names would elicit a similarly low level of activation in the parietal region because neither of these two types of stimuli involves numbers. It should be noted that, as mentioned above, there are different types of quantifiers such as numerical, logical, first-order, higher order, frequency adverbs, and quantity pronouns and nouns [McMillan et al., 2005, 2006; Morgan et al., 2011; Troiani et al., 2009]. When numerical quantifiers are included the stimulus set, the processing of numbers (e.g. "3" in the quantifier "more than 3") may confound the results because it is difficult to determine whether the brain responds to the whole quantifiers or to the numbers in the quantifiers. Therefore, to provide a clean test of the notation-dependent versus notation-independent hypotheses, this study used quantifiers without actual numbers (i.e., frequency adverbs and quantity pronouns and nouns, see Methods section for details).

METHODS

Participants

A total of 20 healthy right-handed undergraduates (mean age = 20.6 years and range = 18.8–22.5 years) were recruited from Beijing Normal University. Half of them were male. Participants had no history of neurological or psychiatric disorders or head injury. Informed written consent was obtained from each participant after the procedures of the experiment were explained. This study was approved by the Institutional Review Board of the Imaging Center for Brain Research in the Institute of Cognitive Neuroscience and Learning at Beijing Normal University.

Materials, Experimental Design, and Procedure

To investigate brain activation for the semantic processing of quantifiers, animal names and numbers, we used the semantic distance judgment task [Mummery et al., 1998; Zannino et al., 2006]. Six types of materials were used in this study: frequency adverbs (e.g., always, often, and frequently), quantity pronouns/nouns (e.g., many, some, and few), Arabic digits, animal names (e.g., tiger, leopard, and sheep), number words, and dot arrays (see Appendix).

For each trial, one target item was presented in the upper part of the screen, and two optional items were shown in the lower part (one at the left side and the other at the right side). Participants were asked to choose the one that had the smaller semantic distance from the target item. For example, one trial had "some" as the target item and "many" and "myriad" as optional items. Participants should choose "many" as the correct answer, because "some" is semantically closer to "many" than to "myriad." For the dot arrays, semantic relation was defined as closeness in number of dots, although participants did not know the exact number of dots for each array. There were 27 trials for each type of materials (or condition). To minimize the practice effect across conditions (i.e., Arabic digits, number words, and dot arrays), we did not use the same numerical values for the three conditions.

Scanning was done in three runs with a block design. Each run included six task blocks (36 s per block) separated by six blocks of resting (24 s per block). Each task block included nine trials (4 s per trial) per condition.

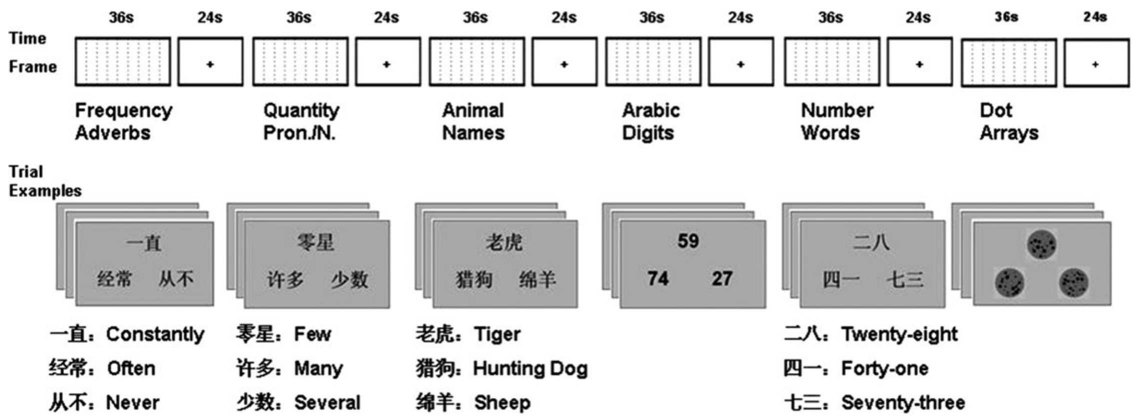

Figure 1.
The experimental procedure and examples of stimuli in this study. Each participant was scanned in three 6-min runs. Each run contained six task blocks (one block of nine trials for each type of material) and six fixation blocks. The order of the six blocks was arranged in a balanced Latin square design. pron.: pronoun and n: noun.

Each condition occurred only once within a run. The experimental procedure is represented in Figure 1.

The order of trials in each task block was randomized for each participant. The task blocks were arranged according to a balanced Latin-square design. For the task blocks, participants were asked to press a button to choose the correct answer as quickly and accurately as possible. For the resting blocks, participants were requested to view the fixation sign "+" at the center of the screen. Before the scanning, participants were given practice trials. The entire experiment lasted about half an hour.

Apparatus and Imaging Parameters

Stimulus presentation and behavioral data recording were controlled by a program developed using Microsoft Visual Basic on an IBM ThinkPad laptop. The stimuli were projected onto a translucent screen placed at the back of the magnet bore. Participants viewed the screen, at a distance of about 30 cm from the eyes, through a mirror mounted on the head coil.

Imaging was performed on a Siemens 3T Trio scanner (Munich, Germany) using a standard eight-channel head coil. After automatic shimming of the magnetic field, a three-dimensional high-resolution T1 anatomical image was acquired for coregistration with the functional images. Next, functional volumes were acquired using a multiple slice T2*-weighted echo planar imaging sequence. The following parameters were used: repetition time = 2000 ms; echo time = 30 ms; flip angle = 90°; matrix dimensions = 64×64; field of view = 200 mm; slice thickness = 4 mm. A total of 32 slices covered the entire brain.

Image Processing and Statistical Analysis

Individual fMRI 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 to correct for whole-brain differences over time. Afterward, images were smoothed using an isotropic Gaussian kernel of 8 mm and a high-pass filter at a cutoff of 128 s.

We calculated parameter-estimated images for individual participants across the whole brain. We then conducted group analyses with random effects on the brain activation maps of all participants. There were three steps for the group analyses. We first calculated the brain activation for each condition relative to fixation. The contrasts

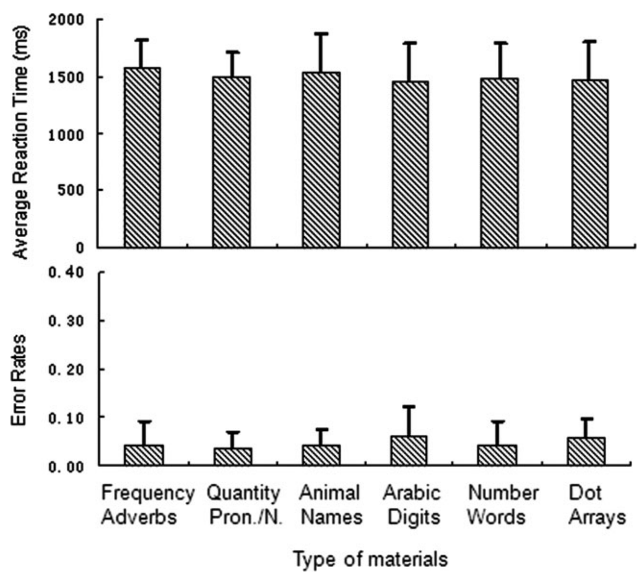

Figure 2.
Mean reaction time (ms) and error rates by types of materials. pron.: pronoun and n: noun.

TABLE I. Loci of brain activation for six types of materials

Type of material	Brain region	*t* value	Volume	Coordinates		
Frequency adverbs	Right middle occipital gyrus	14.59	4976	27	−93	6
		13.4		−18	−99	0
		12.67		−21	−90	3
	Left supplementary motor area	11.14	284	−6	15	51
	Left precentral gyrus	10.83	1172	−42	6	33
		9.45		−27	−3	48
		8.92		−45	21	27
	Right middle frontal gyrus	6.11	102	39	3	66
		6		30	0	51
		5.99		39	−3	48
Quantity pron./n	Left inferior parietal gyrus	14.28	902	−27	−54	42
		8.81		−45	−39	42
	Right middle occipital gyrus	12.96	3833	24	−96	6
		12.79		18	−102	12
		12.69		−21	−99	9
	Left precentral gyrus	11.88	1667	−42	3	30
		9.1		−30	24	3
		9.07		−33	0	48
	Right inferior parietal gyrus	9.63	338	30	−60	48
		6.29		42	−42	45
	Right precentral gyrus	6.87	157	45	3	30
		6.24		33	−3	39
		5.85		33	−3	48
Animal names	Left superior parietal gyrus	10.72	796	−27	−60	45
		9.75		−27	−48	39
		4.79		−3	−72	45
	Right calcarine gyrus	10.56	2837	24	−96	3
		9.18		9	−75	−27
		8.81		−24	−93	9
	Right superior parietal gyrus	8.87	422	27	−60	45
		6.14		21	−72	57
		5.9		39	−42	42
	Left inferior frontal gyrus	8.71	869	−45	9	30
		8.29		−45	21	27
		7.92		−27	−3	51
Arabic digits	Left superior parietal gyrus	14.17	3948	−27	−63	48
		10.28		27	−60	48
		9.71		−15	−99	9
	Left middle frontal gyrus	9.23	754	−24	−3	51
		9.19		−45	6	27
		8.15		−9	12	51
	Right insula	8.32	124	30	21	3
	Left insula	7.18	117	−30	21	3
		5.77		−30	27	12
Number words	Left superior parietal gyrus	14.71	5818	−27	−63	51
		13.53		−27	−54	45
		12.75		−33	−48	42
	Left inferior frontal gyrus	10.47	474	−45	6	27
		7.31		−30	21	6
		6.42		−45	21	27
	Left supplementary motor area	9.06	143	−6	9	54
		6.37		12	12	51
		5.94		9	21	48
	Left middle frontal gyrus	8.41	231	−27	−3	51
		6.95		−39	0	63

TABLE I. (Continued)

Type of material	Brain region	t value	Volume	Coordinates		
Dot arrays	Left middle occipital gyrus	17.84	6417	−15	−99	9
		17.45		15	−102	12
		17.2		18	−99	0
	Right inferior frontal gyrus	11.46	229	51	9	27
		7.02		60	12	39
	Left inferior frontal gyrus	8.45	147	−45	6	27
	Right middle frontal gyrus	6.98	136	48	33	24
	Left supplementary motor area	6.39	102	−6	15	51
		6.04		9	18	51
	Right precentral gyrus	6.37	103	36	−3	51

Height threshold: $t = 4.65$, $P < 0.00001$, and uncorrected. Extent threshold: $k = 50$ voxels. Voxel size: $3 \times 3 \times 3$ mm^3.

between the six conditions were then conducted with a lenient threshold, $P < 0.01$. Finally, to reveal the regions that were significantly activated by different tasks, we conducted conjunction analyses [Friston et al., 1999; Price and Friston, 1997]. The minimum T-field was computed across different tasks. The voxels that were significant in all tasks were retained. Conjunction analyses on selected contrasts (see Results section for specific contrasts) were conducted to show (1) number- and numerosity-related brain activations, (2) quantity-related brain activations, and (3) quantifier-related brain activations.

RESULTS

Behavioral Results

The averaged reaction time and error rates for each condition are shown in Figure 2. Analysis of variance with repeated measures (six conditions) revealed that the condition or material type had no significant effect on either the reaction time [F (1, 19) = 1.24, $P = 0.304$] or the error rates [F (1, 19) = 0.05, $P = 0.831$].

Imaging Results

The activation patterns for the six conditions relative to fixation are presented in Table I and Figure 3. In the following paragraphs, we summarize the results from the conjunction analyses.

Number- and numerosity-related brain activations

Based on the conjunction analysis of contrasts "Arabic digits – animal names," "number words – animal names," and "dot arrays – animal names," numbers, and numerosities (i.e., Arabic digits, number words, and dot arrays) showed notation-independent processing at the right IPS ($P < 0.01$, voxel = 20, uncorrected, see the top panel of Figure 4).

Quantity-related brain activations

The conjunction analysis of contrasts "Arabic digits – animal names," "number words – animal names" and "dot arrays – animal names," "frequency adverbs – animal names," and "quantity pron./n – animal names" showed that no brain regions were significantly activated when quantity is broadly defined to include that of quantifiers as well as that of numbers and numerosities ($P < 0.01$, voxel = 20, and uncorrected; see the bottom panel of Figure 4). In other words, there were no quantity-related brain activations shared by quantifiers, numbers, and numerosities.

Quantifier-related brain activations

Relative to Arabic digits, number words, and dot arrays, quantifiers (i.e., frequency adverbs and quantity pronouns and nouns) elicited more activation in the left middle temporal gyrus and inferior frontal gyrus, based on the conjunction analysis of contrasts "frequency adverbs – Arabic digits," "frequency adverbs– number words," "frequency adverbs – dot arrays," "quantity pron./n – Arabic digits," "quantity pron./n – number words," and "quantity pron./n – dot arrays," ($P < 0.01$, voxel = 20, and uncorrected; see the top panel of Figure 5). Additionally, numbers and numerosities (i.e., Arabic digits, number words, and dot arrays) elicited more activation in the right IPS than quantifiers (i.e., frequency adverbs and quantity pronouns and nouns), based on the conjunction analysis of contrasts "Arabic digits – frequency adverbs," "number words – frequency adverbs," "dot arrays – frequency adverbs," "Arabic digits – quantity pron./n," "number words – quantity pron./n," and "dot arrays – quantity pron./n" ($P < 0.01$, voxel = 20, and uncorrected; see the bottom panel of Figure 5).

DISCUSSION

The objective of this study was to investigate whether the quantity processing of quantifiers (frequency adverbs and quantity pronouns/nouns), numbers (Arabic digits and number words), and numerosities (dot arrays) shared the same neural correlates in the IPS. Quantifiers did not produce greater activation in the IPS than did the control material of animal names. In contrast, numerical materials (i.e., Arabic digits and number words) and dot arrays consistently induced greater activation in the IPS region than

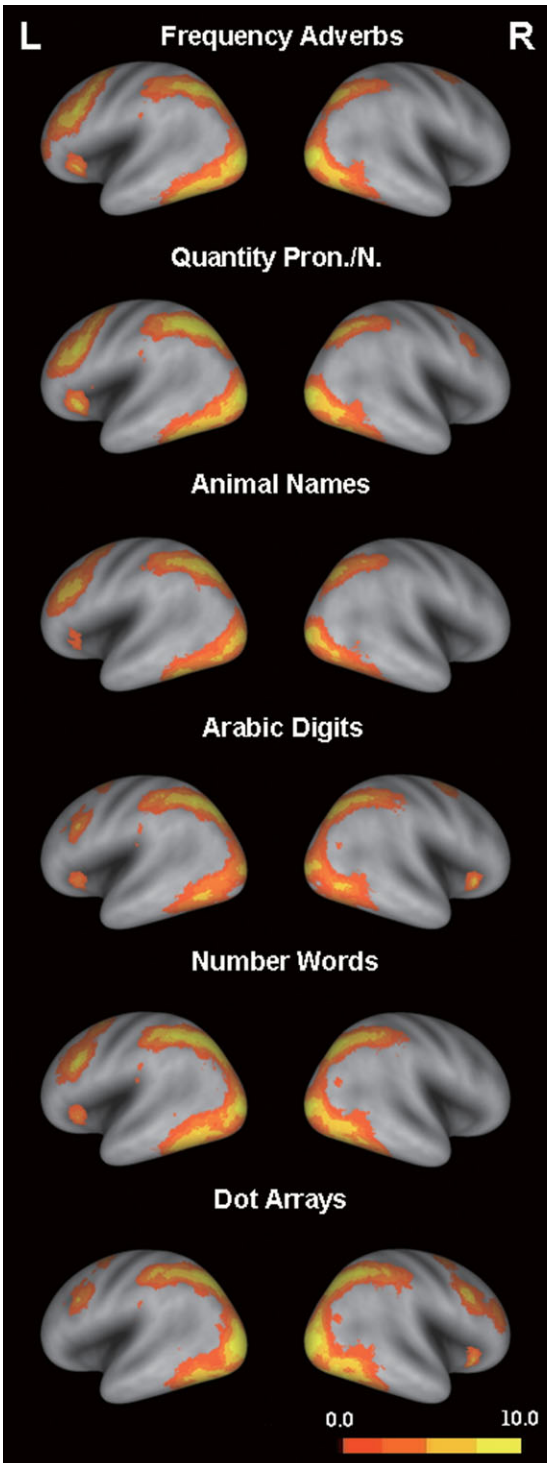

Figure 3.
Brain activation for the six types of materials relative to fixation. Clusters that survived $P < 0.00001$ (uncorrected) with spatial extent $k > 50$ voxels were considered statistically significant. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

did animal names and quantifiers. These results suggest a clear neural dissociation between the quantity processing of quantifiers and that of numbers and numerosities.

This dissociation between the quantity processing of quantifiers and that of numbers and numerosities is evidence against the abstract quantity hypothesis (or the notation-independent hypothesis) in the IPS. According to the abstract quantity hypothesis, the activation of quantity processing of quantifiers should be similar to the activation of quantity processing of numbers and dot arrays in the IPS. We compared quantifiers, numbers, and dot arrays with a control semantic task (animal names). This was done because an earlier study found that number comparison tasks differed from the processing of animal names (animals varying in ferocity) in the bilateral IPS [Thioux et al., 2005]. Our results showed greater activations in the IPS for numbers and dot arrays than for both quantifiers and animal names. It appears that the quantity

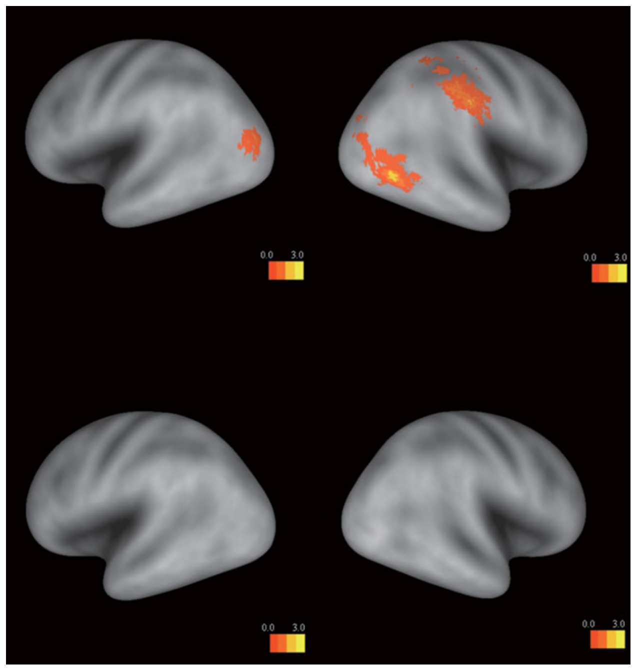

Figure 4.
Number words, Arabic digits, and dot arrays elicited greater activation than animal names in the right IPS based on the conjunction analysis of contrasts "Arabic digits – animal names," "number words – animal names," and "dot arrays – animal names" ($P < 0.01$, voxel = 20, uncorrected, and the top panel). Quantifiers (frequency adverbs and quantity pronouns/nouns) did not show any notation-independent processing at the parietal cortex based on the conjunction analysis of contrasts "Arabic digits – animal names," "number words – animal names" and "dot arrays – animal names," "frequency adverbs – animal names," and "quantity pron./n – animal names" ($P < 0.01$, voxel = 20, uncorrected, and the bottom panel). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

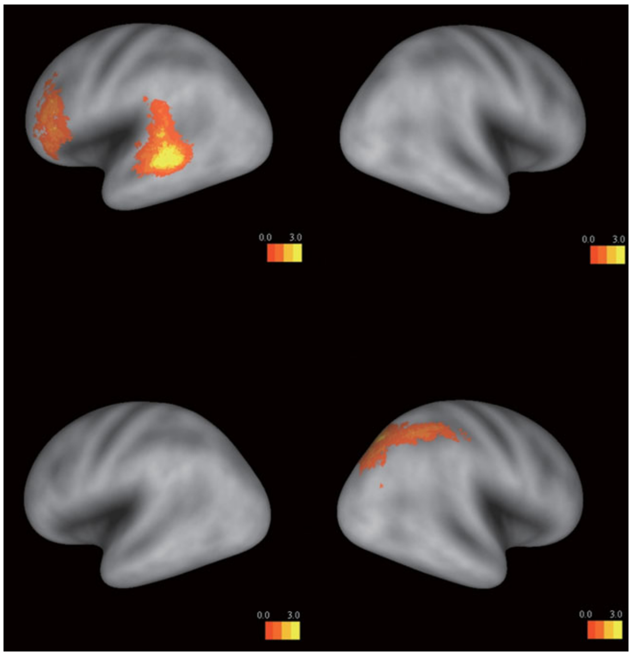

Figure 5.
Quantifiers elicited more activation in the left middle temporal gyrus and inferior frontal gyrus than numbers and numerosities based on the conjunction analysis of contrasts "frequency adverbs – Arabic digits," "frequency adverbs– number words," "frequency adverbs – dot arrays," "quantity pron./n – Arabic digits," "quantity pron./n – number words," and "quantity pron./n – dot arrays" ($P < 0.01$, voxel = 20, uncorrected, and the top panel). Numerical materials elicited more activation in the right IPS than quantifiers based on the conjunction analysis of contrasts "Arabic digits – frequency adverbs," "number words – frequency adverbs," "dot arrays – frequency adverbs," "Arabic digits – quantity pron./n," "number words – quantity pron./n," and "dot arrays – quantity pron./n" ($P < 0.01$, voxel = 20, uncorrected, and the bottom panel). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

processing of numbers and dot arrays is subserved by the IPS, but the quantity processing of quantifiers is not. In other words, the IPS may be specific to the processing of numbers and dot arrays, rather than quantity processing in general. These results supported the hypothesis of notation-dependent quantity processing in the brain.

Quantifiers were found to produce greater activation than Arabic numbers, number words and dot arrays only in the left middle posterior temporal gyrus and the left inferior frontal gyrus. These regions are associated with general semantic processing and verbal processing [Booth et al., 2006]. Thus, the quantity processing of quantifiers may share similar neural mechanisms as general semantic and verbal processing.

The dissociation between quantifier and number processing was consistent with some of the previous neuropsychological studies. These studies found that patients who had damages to their parietal cortex showed impairment in number processing but retained the ability for quantifier processing [Cipolotti et al., 1991; Morgan et al., 2011]. For example, Cipolotti et al. [1991] found that the patient with damage to her parietal cortex could not complete the simplest arithmetic problems and multiplication table, but she could judge which of two measure terms had greater quantity information (e.g. gram, kilo, meter, and centimeter). Morgan et al. [2011] found that corticobasal degeneration patients had a selective deficit for cardinal quantifiers (e.g., "The blonde lady is holding more than three flowers") compared to healthy seniors, but the processing of logical quantifiers (e.g., "There are some orange pumpkins in the red truck") was normal. These studies showed neural dissociation in quantifier and numerical processing.

Our results, however, appeared to be different from several other neuropsychological studies that found a close association between quantifier processing and number processing [Cappelletti et al., 2006; McMillan et al., 2006; Morgan et al., 2011; Polk et al., 2001; Troiani et al., 2011]. Some of the discrepancies may have been due to the use of materials. For example, the quantifiers used by Polk et al. [2001] included words such as "dozen," "pair," "twin," "half," "quartet," and "sextet." These words appear to contain specific number information (12, 2, etc.), which might have accounted for the similarity between their semantic processing and that of numbers. Similarly, the studies of the corticobasal degeneration patients [e.g., McMillan et al., 2006; Morgan et al., 2011; Troiani et al., 2011] also used quantifiers that contained actual numbers (numerical or cardinal quantifiers such as "more than three"). Similarly, Troiani et al.'s [2009] finding that numerical quantifiers induced greater activation in the parietal lobe than did logical quantifiers can be explained by the number words embedded in their numerical quantifiers (e.g., "at least three" and "more than two"). In sum, previous neuroimaging studies used both numerical and non-numerical quantifiers, which makes it difficult to distinguish whether the brain is processing the whole phrases as one unit (i.e., the whole quantifiers only) or the components (i.e., both the quantifiers and the specific numbers). In our study, we excluded any quantifiers that include actual numbers to investigate how "pure" quantifiers are processed and to provide a clean test of the notation-dependent and -independent hypotheses. It seems clear from both Troiani et al. study and our study that "pure" quantifiers (or logical quantifiers in Troiani et al.) are not processed in the IPS but are rather processed in the brain's language areas. These results also suggest that it is important to distinguish quantifiers with and without numbers. We should hasten to add that, because we did not include a condition with numerical quantifiers, the above discussion is speculative. Future research should compare directly quantifiers with and without explicit numbers.

Finally, our finding on surface may lead to the question whether non-numerical quantifiers (including logical quantifiers) would have any quantity information. However, as we argued in Introduction section, quantifiers in natural language contain information of quantity [Hubbard et al., 2008; Rajapakse et al., 2005], denote numerical concepts without explicit specification of an exact number [Cappelletti et al., 2006], and serve as a language-based counting system for tribal people without a formal number-based system [Pica et al., 2004].

In summary, this study found neural dissociations for the processing of quantifiers, numbers, and numerosities. Although the quantity processing of numbers and numerosities relies on the IPS, the quantity processing of quantifiers without actual numbers relies on the left inferior frontal gyrus and the left middle temporal gyrus. The results of this study suggest that the IPS is not the only brain region for all types of quantity processing, which is consistent with the growing literature that semantics are supported by distributed networks [Patterson et al., 2007].

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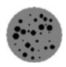
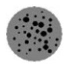
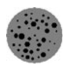
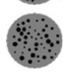
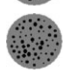
APPENDIX: MATERIALS FOR SEMANTIC PROCESSING IN THIS STUDY

Conditions	Chinese name	Pronunciation	English	Word frequency[a]
Frequency adverbs	总是	zǒng shì	always	254.93
	一直	yī zhí	constantly	731.85
	经常	jīng cháng	often	100.28
	时常	shí cháng	frequently	4.92
	有时	yǒu shí	sometimes	77.12
	偶尔	ǒu ěr	occasionally	20.15
	从不	cóng bù	never	15.59
Quantity pronouns/nouns	无数	wú shù	myriad	19.50
	大量	dà liàng	abundance	25.04
	许多	xǔ duō	many	60.04
	一些	yī xiē	some	510.72
	少数	shǎo shù	several	7.15
	零星	líng xīng	few	0.51
	没有	méi yǒu	none	3226.48
Animal names	老虎	lǎo hǔ	tiger	10.97
	豹子	bào zi	leopard	1.07
	老鹰	lǎo yīng	eagle	7.48
	猎狗	liè gǒu	hunting dog	1.82
	水牛	shuǐ niú	buffalo	3.19
	绵羊	mián yáng	sheep	2.71
	兔子	tù zi	rabbit	23.76
Number words	二八	èr shi bā	twenty-eight	
	三七	sān shi qī	thirty-seven	
	四一	sì shi yī	forty-one	
	五九	wǔ shi jiǔ	fifty-nine	
	六二	liù shi èr	sixty-two	
	七三	qī shi sān	seventy-three	
	八五	bā shi wǔ	eighty-five	
Arabic digits	27	èr shi qī	twenty-seven	
	36	sān shi liù	thirty-six	

APPENDIX (Continued)

Conditions	Chinese name	Pronunciation	English	Word frequency[a]
	42	sì shi èr	forty-two	
	59	wǔ shi jiǔ	fifty-nine	
	65	liù shi wǔ	sixty-five	
	74	qī shi sì	seventy-four	
	83	bā shi sān	eighty-three	
Dot arrays	 (20)			
	 (25)			
	 (30)			
	 (35)			
	 (40)			
	 (45)			
	 (50)			

[a]The word frequency (per million) for frequency adverbs, quantity pronouns/nouns, and animal names came from the SUBTLEX-CH (Cai and Brysbaert, 2010).