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Neural correlates of quantity processing of Chinese numeral classifiers

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ABSTRACT

Linguistic analysis suggests that numeral classifiers carry quantity information. However, previous neuroimaging studies have shown that classifiers did not elicit higher activation in the intraparietal sulcus (IPS), associated with representation of numerical magnitude, than tool nouns did. This study aimed to control the semantic attributes of classifiers and reexamine the underlying neural correlates. Participants performed a semantic distance comparison task in which they judged which one of the two items was semantically closer to the target. Processing classifiers elicited higher activation than tool nouns in the bilateral inferior parietal lobules (IPL), middle frontal gyri (MFG), right superior frontal gyrus (SFG), and left lingual gyrus. Conjunction analysis showed that the IPS was commonly activated for classifiers, numbers, dots, and number words. The results support that classifiers activate quantity representations, implicating that the system of classifiers is part of magnitude cognition. Furthermore, the results suggest that the IPS represents magnitude independent of notations.

1. Introduction

In a classifier language like Chinese, an additional element is essential when a noun (N) is quantified by a numeral (Num). This additional element is known as a numeral classifier. As shown in Table 1, numeral classifiers come in two varieties, sortal classifiers (C) and mensural classifiers (M). Note that there are a number of alternative names for the two, e.g., classifiers and measure words, classifiers and massifiers, count-classifiers and mass-classifiers, etc. Suffice to say that making the distinction within the category of numeral classifiers is far more important than the particular terms used. We will thus use the abbreviations C and M for this distinction and C/M for the category of numeral classifiers.

Though it has been controversial whether C and M belong to the same grammatical category, C and M clearly converge syntactically as they always appear in the same grammatical position and are mutually exclusive (e.g., He, 2008; Her 2012b; Hsieh, 2008), but C and M diverge semantically in the sense that Cs qualify the noun but Ms quantify the noun (e.g., Her & Hsieh, 2010; Li, 2012). Her (2012a) indicated that in the nominal phrase [Num C/M N], C is semantically redundant but M is semantically substantive, and proposed an innovative interpretation in terms of the mathematical relation between Num and C/M. The precise formulation he offered is: **[Num X N] = [[Num × X] N], where X = C if and only if X = 1, otherwise X = M** (Her, 2012a:1679). Given the multiplicative function between Num and C/M, **i.e., [Num × C/M]**, C and M converge as multiplicands but diverge in terms of their respective values, i.e., C = 1, M ≠ 1.

Her and Wu (2017) further classified Ms into four subcategories according to the types of mathematical values they encode (Table 2). While M_1 and M_2 both encode numerical values, the former has fixed values and the latter does not. Likewise, M_3 and M_4 both encode non-numerical values, but the former has fixed values and the latter does not. Thus, C, M_1 and M_3 encode fixed values, while M_2 and M_4 do not.

While Her's (2012a) multiplicative theory of C/M is based on the premise that numerals and C/Ms are closely related, it is still controversial whether language and mathematics belong to two independent domains or are related in some aspects. While the two seem to involve distinct cognitive abilities, both represent concepts by symbols (e.g., number words, Arabic numbers, and arithmetic operations, etc.). Psychologists have thus investigated whether the form of neural representation of number is notation-independent (e.g., Dehaene, Dehaene-Lambertz, & Cohen, 1998; McCloskey, 1992) or notation-specific (e.g., Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007).

Neuropsychological studies (e.g., Butterworth, Cappelletti, & Kopelman, 2001; Cappelletti, Butterworth, & Kopelman, 2006;

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Table 1
Examples of sortal and mensural classifiers.

Sortal classifiers (C)			Mensural classifiers (M)		
三	本	雜誌	三	箱	雜誌
san	*ben*	*zazhi*	*san*	*xiang*	*zazhi*
3	C	magazine	3	M-box magazine	
'3 magazines'			'3 boxes of magazines'		
三	個	蘋果	三	公斤	蘋果
san	*ge*	*pingguo*	*san*	*gongjin*	*pingguo*
3	C	apple	3	M-kilo	apple
'3 apples'			'3 kilos of apples'		

Table 2
Types of mathematical values denoted by C/Ms.

Numerical	Fixed	**n = 1** e.g., *ben* (本), *ke* (顆), *tiao* (條), *zhi* (隻)	C
		n = 2 e.g., *duei* (pair 對); **n = 12** e.g., *da* (dozen 打)	M_1
	Variable	**n > 1** e.g., *pai* (row 排), *zu* (group 組), *die* (stack 疊)	M_2
Non-numerical	Fixed	e.g., *gongjin* (kilogram 公斤), *gongli* (kilometer 公里)	M_3
	Variable	e.g.,*chi* (spoon 匙), *dai* (bag 袋), *bei* (cup 杯)	M_4

Cipolotti, Warrington, & Butterworth, 1995) and neuroimaging studies (e.g., Cui et al., 2013; Wei, Chen, Yang, Zhang, & Zhou, 2014) tapped into this question by examining the neural basis in processing number words, quantifiers, classifiers, and numbers. In Butterworth et al. (2001), a semantic dementia patient, who had left temporal lobe atrophy, encountered severe impairment in linguistic abilities and general knowledge while preserving intact mathematical abilities. This patient performed remarkably well at reading and spelling number words, whereas he was unable to read or spell non-number words. Cappelletti et al. (2006) also described a semantic dementia patient who selectively possessed intact understanding of quantifiers (e.g., *many*, *a few*) only. Likewise, this patient showed the ability in the comprehension of numerical knowledge but not linguistic concepts. These results suggested that the semantic processing of numerical knowledge is functionally and neuroanatomically distinct from non-numerical knowledge and is notation-independent.

Nevertheless, inconsistent results are found in other studies, e.g., Cipolotti et al. (1995) and Wei et al. (2014). Cipolotti et al. (1995) reported an acalculic patient who was able to read letters, words, and number words but not Arabic numbers, suggesting that number processing is notation-dependent. Notably, Cipolotti et al. (1995) also found that the patient's knowledge of cardinal value of Arabic numbers was intact in magnitude comparison tasks. This suggested that although the number processing is notation-dependent, the processing of semantic quantity may not be notation-dependent. Wei et al. (2014) compared the brain activations of semantic processing of quantifiers (e.g., frequency adverbs and quantity pronouns), words (e.g., animal names), Arabic numbers, and dot arrays with functional magnetic resonance imaging (fMRI). They found that processing of numbers and dot arrays activated more in the right intraparietal sulcus (IPS), which plays an important role in representation of numerical magnitude (Dehaene, Piazza, Pinel, & Cohen, 2003; Nieder & Dehaene, 2009), whereas the processing of quantifiers elicited greater activations in the left middle temporal gyrus (MTG) and the left inferior frontal gyrus (IFG) that are usually associated with general semantic processing (Booth et al., 2006).

Similar results were obtained from the very first fMRI study on quantity processing of Chinese numeral classifiers by Cui et al. (2013).[1] They compared the processing of classifiers with that of tool nouns, numbers, and dot arrays in a semantic distance comparison task, where participants had to judge which one of the two items was semantically closer to the target item. They reported that classifiers, tool nouns, numbers, and dot arrays commonly activated in the right IFG, right angular gyrus, right supplementary motor area, right precentral gyrus, left insula, left cerebellum, and bilateral lenticular nucleus. They found that classifiers and tool nouns elicited greater activation in the left IFG and the left MTG than numbers and dot arrays. They did not find that classifiers elicited more activations than tool nouns in the IPS which has been shown to play an important role in processing and representation of numerical magnitude (Dehaene et al., 2003; Nieder & Dehaene, 2009). The aim of our study is thus to reexamine the neural correlates of quantity processing of Chinese numeral classifiers.

One possible critical reason why Cui et al. (2013) did not find the IPS more activated for processing classifiers than tool nouns may be that they did not make the crucial distinction between C and M. Nor did they make the distinction between numerical and non-numerical C/Ms. The term "classifier" they used referred to both C and M in their study. As reviewed above, linguistic studies suggested that Cs differ significantly from Ms and Ms can be further classified, according to Her and Wu (2017), into four categories along two dimensions: numerical vs. non-numerical and fixed vs. variable (Table 2). The processing of numerical and non-numerical C/Ms may vary significantly.

Also, Cui et al. (2013) did not explain how they selected and arranged the stimuli for each trial in the semantic distance comparison task. Thus, they may not have controlled the potential confounding effect of the semantic attributes of C/Ms, which may have been another reason why they did not find the IPS more activated for processing C/Ms than processing tool nouns. To be more specific, Chinese Cs are based on a range of semantic attributes such as human, animacy, shape, function, etc. Cs thus function as a profiler in highlighting an inherent semantic feature of the noun (Her, 2012a; Tai & Wang, 1990). For example, there are at least three different Cs that are compatible with the noun *yu* (fish): *zhi* emphasizes the feature of animacy, *tiao* highlights the long shape, and *wei* profiles the tail (Her, 2012a:1673–1674). Accordingly, it is possible that, aside from the mathematical values of C/Ms, the semantic attributes of C/Ms play a role in processing C/Ms. Thus, that the confounding factor of C/M's semantic attributes was not controlled in the fMRI study by Cui et al. (2013) may also explain the higher activation in brain regions that are related with general semantic processing such as the left IFG and the left MTG.

The purpose of our study was to replicate the fMRI experiment by Cui et al. (2013), but with a modified paradigm which controlled the confounding factors. We expected to see that C/Ms and numbers induce more activation in the IPS compared with tool nouns.

Prior to the fMRI experiment, we conducted two behavioral experiments with semantic distance comparison tasks to clarify how the variables mentioned above influenced the processing of C/Ms. In the first experiment, we examined how semantic attributes of C/Ms influenced processing. Participants had to decide which one of the two C/M phrases at the bottom of the screen was semantically closer to the target C/M phrase on top. Results showed that participants preferred the one with comparable semantic attributes over the one with a closer mathematical value. This suggested that a C/M's semantic attributes affected processing, and this thus was likely a confounding factor not controlled in the fMRI study by Cui et al. (2013).

[1] While non-classifier languages have no syntactic category of C/M, the semantic concept of Ms exists cross-linguistically. English, and other non-classifier languages, may thus have words of measure such as *pair*, *group*, and *kilo* that are nouns syntactically. (*footnote continued*) Numerals, on the other hand, are available in nearly all languages, and are considered part of quantifiers, e.g., *a lot*, *many*, and *few*. However, grammatical number markers, e.g., the suffix /-s/ in English, and sortal classifiers, or Cs, are largely mutually exclusive in a noun phrase, in the few languages that employ both. This fact has led to a controversial view that C and grammatical number belong to the same syntactic category. Relevant to our study is the fact that C/Ms, numerals, quantifiers, and plural markers all carry quantity information.

Therefore, we conducted a second experiment and controlled the semantic attributes of C/M by using minimal pairs as stimuli (Her, Chen, & Yen, 2017). An example of a minimal pair is *yi qun shashou* (one group of killers) and *yi bang shashou* (one gang of killers), where the identical human noun *shashou* (killer) confines the semantic attributes of the two Ms in the two nominal phrases, which thus differ minimally only in terms of the mathematical values the two Ms encode. Consequently, the judgment whether *yi qun shashou* (one group of killers, $n > 1$) or *yi bang shashou* (one gang of killers, $n > 1$) is semantically closer to *yi dui shashou* (one team of killers, $n > 1$) must be based on this variable alone. For example, if a participant reported that his/her subjective mathematical values of *yi dui* (one team of), *yi qun* (one group of), and *yi bang* (one gang of) were 10, 20, and 30, respectively, the correct answer of this trial for this participant would be *yi qun shashou* (one group of killers) instead of *yi bang shashou* (one gang of killers), as 20 is closer to 10 than 30 is. Results showed that participants performed better for C/Ms with fixed values than those with variable values (Her et al., 2017).

Therefore, in order to better examine the neural correlates of C/Ms in the fMRI study, we developed a modified paradigm based on these behavioral findings and used minimal pairs of phrases with C/Ms of fixed values. Given previous findings that the IPS represented number independent of notations (Dehaene et al., 1998, 2003), we expected to find greater activations in the IPS for processing C/Ms than tool nouns by adopting our modified paradigm.

2. Method

2.1. Participants

Twenty-six native speakers of Mandarin (14 males, mean age = 23.23 ± 2.35 years) were recruited from National Chengchi University. All participants were right-handed. They had normal or corrected-to-normal vision and had no history of neurological or psychiatric disorders or contraindications to MRI. Before the experiment started, they gave written informed consent to the study approved by the Research Ethics Committee of National Taiwan University.

2.2. Stimuli and materials

We conducted a within-subject design and manipulated two variables. The two independent variables were comparison (C/Ms vs. tool nouns) and C/M type (numerical vs. non-numerical). The four main experimental conditions were C/M comparison with numerical stimuli, C/M comparison with non-numerical stimuli, tool noun comparison with numerical stimuli, and tool noun comparison with non-numerical stimuli (see Fig. 1 gray part). The nominal phrases consisted of a numeral (the number "one"), a C or M, and a tool noun. Including the numeral in the phrase enabled participants to process the C/M in the phrase correctly as C/M instead of other meanings.

There were five other conditions: baseline, numbers, dots, number words, and tool nouns. We modified the baseline condition in Cui et al. (2013), which was the rest (fixation). In this study, the baseline condition contained three identical nominal phrases for each trial. In this case, participants still had to process the stimuli that were visually as complicated as the ones in the main four experimental conditions (see Appendix A for all experimental stimuli). Consequently, we could examine the brain activations involved in processing C/Ms or tool nouns by contrasting the four main experimental conditions against the baseline condition. Following the paradigm by Cui et al. (2013), we further included conditions of numbers, dots, number words, and tool nouns to investigate the neural correlates that commonly activated during number processing (C/M comparison, numbers, dots, number words) and semantic processing (tool noun comparison and tool nouns).

The number of strokes, frequency of C/Ms, and frequency of nouns were carefully matched among the four main experimental conditions and the baseline condition (Appendix B). The word frequency was obtained from the Digital Resources Center for Global Chinese Language Teaching and Learning (Cheng et al., 2005).

For the conditions of C/M comparison, numbers, dots, and number words, the number of the target item was larger or equal to the answer for one third of the trials; the number of the target item was in the middle of the answer and the distractor for one third of the trials; the number of the target item was smaller or equal to the answer for the rest one third of trials. For the conditions of numbers, dots, and number words, the number of the stimuli ranged from 7 to 99.

For the conditions of tool noun comparison and tool nouns, the answer was an item that fell into the same category as the target item. Tool nouns were selected from a set of tool nouns that were categorized into seven categories: constructional material, stationery, clothing and accessories, kitchenware and utensils, weapons, sporting goods, and daily essentials. The conditions of noun comparison and the tool noun condition were composed of two different sets.

2.3. Procedure

We conducted a block design. There were 3 runs in total; each run had 9 blocks. Each block was 36 s followed by a 24-s rest. Each condition had 9 trials per block. In each trial, stimuli displayed for 3.5 s with a 0.5 s inter-trial interval. The order of blocks and trials were randomized. Before scanning, participants completed 18 practice trials and made sure that they were clear about the procedure.

In each trial, participants saw three items on the screen and were asked to judge which one of the two items at the bottom was semantically closer to the target item at the top. Accuracy and speed were both emphasized. If they saw numbers, dots, or number words, they were asked to judge which one of the bottom items had a closer quantity with the target item. They pressed button 1 or 2 to choose the stimuli on the left or right, respectively. They were also told that in order to ensure that they remain focused in the scanner, sometimes they might see three identical items. In this case, i.e. the baseline condition, half of the participants were told to press button 1, whereas the other half were told to press button 2 (Fig. 1).

2.4. fMRI data acquisition

MRI images were collected using a 32-channel head coil in a 3T scanner (Skyra, Siemens Medical Solutions, Erlangen, Germany). A T2*-weighted gradient-echo echo planar imaging (EPI) sequence was used for fMRI scanning, with a 4 mm slice thickness, $200 \times 200\ mm^2$ field of view (FOV), 90° flip angle, 32 axial slices, 2000 ms repetition time (TR), and 30 ms echo time (TE). The anatomical, T1-weighted high-resolution image ($1 \times 1 \times 1\ mm^3$) was acquired using a standard MPRAGE sequence, with a 7° flip angle, 2530 ms TR, 3.3 ms TE and 1100 ms inversion time (TI).

2.5. Statistical analysis of the fMRI data

Preprocessing and statistical analysis of brain images were performed using a statistical parametric mapping 8 (SPM8; Wellcome Trust Center for Neuroimaging, London, UK) software package. The functional images of each participant were corrected for slice timing and head motion and then co-registered to the participant's segmented gray matter image. Next, the images were normalized to the standard Montreal Neurological Institute (MNI) standard space and spatially smoothed by convolution using an 8 mm full width at half maximum Gaussian kernel.

We conducted two random-effect whole-brain analyses. One was a full factorial 2 (C/M vs. noun comparison) by 2 (numerical vs. non-numerical CM) ANOVA with images from the individual-level fixed-effect analysis modelling each condition in contrast to the baseline.

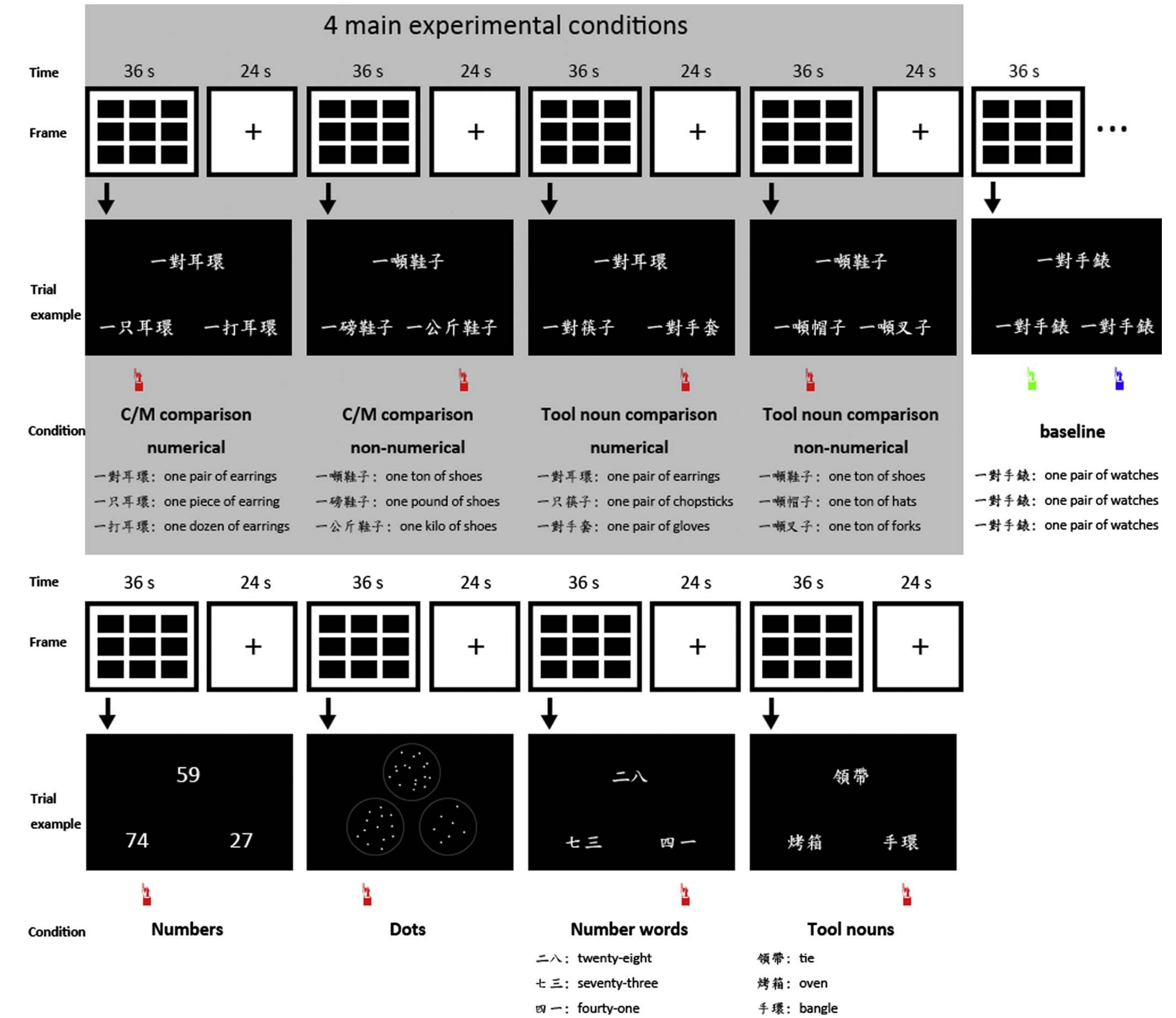

Fig. 1. The experimental procedure and sample trials of each condition in this study. The four main experimental conditions, varying in comparison (C/Ms vs. tool nouns) and C/M type (numerical vs. non-numerical), were shown in the gray part. The other five conditions were baseline, numbers, dots, number words, and tool nouns. There were 3 runs in total; each run had 9 blocks. Each block was 36 s followed by a 24-s rest. Each condition had 9 trials per block. For each trial, participants had to judge which one of the two items at the bottom was semantically closer to the target item. For the conditions of numbers, dots, or number words, participants were asked to judge which one of the bottom items had a closer quantity with the target item. The answer item was indicated with the hand icon. For the baseline condition, in which the three phrases were identical, half of the participants were told to press button 1 (left) and the other half were told to press button 2 (right) to show that they remain concentrated in the scanner.

Then, we conducted contrast analyses for the four main conditions. The other was a one-way ANOVA with images of 9 conditions relative to rest. Consequently, we ran three conjunction analyses to examine the brain regions that co-activate for the four main conditions, five conditions of number processing, and three conditions of semantic processing. The threshold of the statistical maps was at a whole brain voxel-wise intensity of $p_{FWE\text{-}corr} < .05$ (Family-wise error correction). The resulting regions of activation were characterized in terms of their peak voxels in the MNI coordinate space and specified with the automated anatomical labeling.

3. Results

3.1. Participants' exclusion for data analyses

Among the 26 participants, two participants were excluded from data analysis because of data loss and three participants were excluded due to excessive head movement (i.e., whose overall motion was more than 3 mm across the runs or more than 1.5 mm motion between adjacent functional volumes).

3.2. Contrast analyses

Fig. 2A and Table 3 show the results from contrast analyses. First, C/M comparison elicited higher activation than noun comparison in the bilateral inferior parietal lobules (IPL) including the IPS, right superior frontal gyrus (SFG), bilateral middle frontal gyri (MFG), right medial frontal gyrus (mFG), right middle temporal gyrus (MTG), and left lingual gyrus. However, on the other hand, noun comparison did not elicit significantly higher activation than C/M comparison. In addition, the contrast analyses between numerical C + M_1 and non-numerical M_3 did not reveal any significant activation.

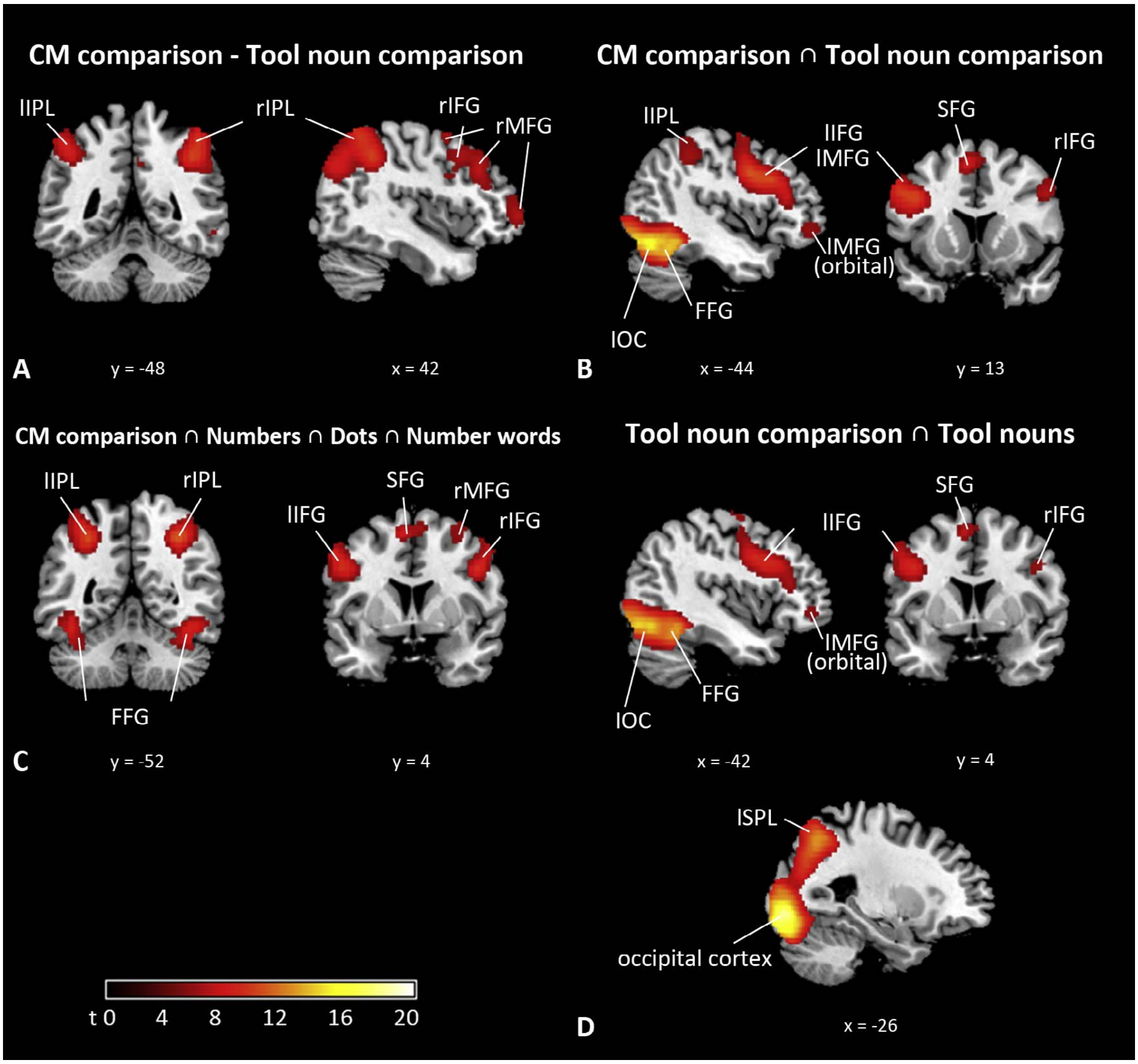

Fig. 2. Brain activations from the contrast analysis and conjunction analysis.

Table 3
Brain activation for contrast analysis between four main conditions, relative to baseline ($p_{FWE\text{-}corr} < .05$; BA, Brodmann's area).

Hemisphere	Brain regions	Peak MNI x	y	z	t-Value	Cluster size
CM comparison – Tool noun comparison						
Right	Inferior parietal lobule (BA 40)	42	−48	44	9.71	3928
Left	Inferior parietal lobule (BA 40)	−44	−52	50	8.69	1343
Right	Superior frontal gyrus (BA 6)	34	4	66	8.64	2544
Left	Lingual gyrus	−18	−88	−12	7.01	122
Right	Middle frontal gyrus (BA 10)	44	54	0	6.78	404
Right	Medial frontal gyrus (BA 8)	4	30	46	5.90	73
Left	Middle frontal gyrus (BA 10)	−40	56	10	5.85	98
Right	Middle temporal gyrus	56	−50	−12	5.65	21
Tool noun comparison – CM comparison						
None						
Numerical C + M_1 – Non-numerical M_3						
None						
Non-numerical M_3 – Numerical C + M_1						
None						

3.3. Conjunction analyses

Conjunction analysis of the four main conditions (processing C/M or tool nouns in nominal phrases with either a numerical C + M_1 or a non-numerical M_3) showed activation in the bilateral inferior occipital cortices (IOC) including the fusiform gyri (FFG), bilateral inferior frontal gyri (IFG, especially in the left hemisphere), left SFG, left MFG (orbital part), and left insula (see Fig. 2B and Table 4).

Conjunction analysis of the five conditions involved in number processing (C/M comparison of numerical C + M_1, C/M comparison of non-numerical M_3, numbers, dots, and number words) showed activation in the IOC including the FFG, bilateral superior parietal lobules (SPL), bilateral inferior parietal lobules, bilateral IFG, right MFG, bilateral SFG, and bilateral insulae (see Fig. 2C and Table 4).

Conjunction analysis of the three conditions involved in semantic processing (two noun comparison conditions and the tool noun condition) showed activation in the bilateral occipital cortices including the FFG, bilateral superior parietal lobules, bilateral IFG (mostly in the left hemisphere), left SFG, and bilateral MFG (see Fig. 2D and Table 4).

4. Discussion

We adopted a modified paradigm that included minimal pairs of C/M with fixed mathematical values to investigate the number processing of C/M with fMRI in this study. We found that processing C/M in a

Table 4
Common brain activation for different types of conditions, relative to rest. ($p_{FWE\text{-}corr} < .05$; BA, Brodmann's area).

Hemisphere	Brain regions	Peak MNI			t-Value	Cluster size
		x	y	z		
CM comparison ∩ Tool noun comparison						
Left	Inferior occipital cortex	−18	−94	−12	20.68	17196
Left	Precentral gyrus (Inferior frontal gyrus, BA 9)	−44	4	34	10.33	3107
Left	Supplementary motor area (Superior frontal gyrus, BA6)	−6	6	58	8.65	533
Right	Precentral gyrus (Inferior frontal gyrus, BA 9)	48	8	34	7.54	509
Left	Middle frontal gyrus, orbital part	−44	46	−4	5.58	116
Left	Insula	−30	20	4	5.53	31
CM comparison ∩ Numbers ∩ Dots ∩ Number words						
Right	Inferior occipital cortex	34	−80	−12	14.51	18,086
Right	Superior parietal lobule (BA 7)	30	−62	52	12.26	
Left	Superior parietal lobule (BA 7)	−24	−62	54	12.05	
Left	Inferior parietal lobule (BA 7, 40)	−30	−52	46	10.04	
Right	Precentral gyrus (Inferior frontal gyrus, BA 9)	50	8	34	9.75	1033
Left	Precentral gyrus (Inferior frontal gyrus, BA 9)	−48	2	36	9.04	1576
Left	Supplementary motor area (Superior frontal gyrus, BA 6)	−6	6	58	8.39	604
Right	Superior frontal gyrus (Middle frontal gyrus, BA 6)	32	−2	62	6.57	302
Right	Insula (BA 45)	32	24	6	5.93	80
Left	Insula (BA 45)	−30	24	6	5.83	64
Tool noun comparison ∩ Tool nouns						
Left	Inferior occipital cortex	−34	−86	−8	16.07	14504
Left	Superior parietal lobule	−28	−64	48	9.93	
Right	Angular gyrus (superior parietal lobule, BA 7)	30	−60	50	7.57	
Left	Precentral gyrus (Inferior frontal gyrus, BA 6, 9)	−42	4	34	8.69	2319
Left	Supplementary motor area (Superior frontal gyrus)	−6	10	56	7.48	334
Right	Precentral gyrus (Inferior frontal gyrus, BA 9)	46	8	34	6.40	194
Left	Middle frontal gyrus, orbital part	−44	46	−4	5.58	92
Right	Middle frontal gyrus	44	28	22	5.39	90

semantic distance task elicited higher activations in the bilateral IPL including the IPS, right SFG, bilateral MFG, right mFG, and right MTG than processing tool nouns. As we predicted, the IPS, which has been shown to frequently engage in numerical representation, was more activated for the contrast of C/M comparison versus tool noun comparison (Dehaene et al., 2003; Nieder & Dehaene, 2009). Moreover, the brain activations in the IPL, SFG, and mFG largely overlapped with the brain regions that were reported in a very recent meta-analysis study of number processing (Sokolowski, Fias, Mousa, & Ansari, 2017). Sokolowski et al. (2017) revealed that not only the parietal lobule but also the frontal regions play an important role in number processing. Specifically, the SFG was repeatedly activated for symbolic magnitude processing while the right mFG and cingulate gyrus were activated for non-symbolic magnitude processing. Moreover, the right SFG consistently activated during symbolic and non-symbolic number processing. Taken together, processing C/M than tool nouns engaged in frontal and parietal regions that have been suggested to associate with processing numerical information. This finding was consistent with the mathematical theory of C/M which proposed that C/M represents mathematical values (Her, 2012a). Although the number of strokes, frequency of C/Ms, and frequency of nouns were carefully matched among the four main experimental conditions and the baseline condition, participants still made more errors while processing C/M compared to processing tool nouns, $t_{(20)} = -3.281$, $p = .004$. One may argue that the activation in the IPS for processing C/M than tool nouns reflected higher task demand rather than magnitude representation in this study. However, it is worth noting that the bilateral IPL were found activated during number proceesing in both active and passive tasks (Sokolowski et al., 2017). This suggests that the activation was related to magnitude processing rather than task demands. However, the function of the bilateral MFG and the rMTG for processing C/M than tool nouns remains unclear and needs further research as these regions were not typical regions that were found to be involved in number processing in the literature.

This finding was different from the finding in the study by Cui et al. (2013), in which the contrast analyses between classifiers and tool nouns resulted in no significant activations. The critical reason why we observed different neural activities of processing classifiers may lie on the nature of classifiers. Chinese classifiers not only have a mathematical function but also function as a profiler. That is, Chinese classifiers not only encode the mathematical values but also highlight the inherent semantic attributes of the noun. However, Cui et al. (2013) overlooked the potential possibility that participants make the semantic judgment based on C/M's semantic attributes which may have confounded their results. As found in the first behavioral experiment that we conducted before this fMRI experiment, participants chose the C/M phrase that had a similar semantic attribute to the target C/M phrase over the C/M phrase that had a similar mathematical value. Therefore, to control for the semantic attributes of C/Ms, we used minimal pairs of C/Ms as our stimuli in this experiment. Adding the same tool nouns in the nominal phrases, i.e. adopting minimal pairs, helped confine the semantic attributes of C/M. Second, we only included the C/M that encode fixed mathematical values, i.e. C, M_1, M_3, in our study whereas Cui et al. (2013) also incorporated C/M with variable mathematical values, i.e. M_2 and M_4, as experimental stimuli. According to the second behavioral experiment we conducted, the accuracy for the variable mathematical value condition was only around 50% and significantly lower than the accuracy for the fixed mathematical value condition in the semantic distance comparison task (Her et al., 2017). In other words, the underlying cognitive mechanism of processing C/M with a variable mathematical value was unclear whereas participants did show that they make semantic judgment based on mathematical values when facing C/M with fixed mathematical values. Consequently, we only included C/M with fixed mathematical in the current experiment. These amendments enabled us to purely examine the neural underpinnings of quantity processing of C/M in this study. Moreover, we further added the baseline condition, in which participants saw three identical nominal phrases that required similar perceptual processing, in this study. By contrasting the four main experimental conditions versus the baseline condition, the resulting brain activations should, at least in part, reveal magnitude representations. In sum, the brain activities for processing the quantity information that C/M encode may only appear for specific stimuli (C/M with a fixed mathematical values) under strictly controlled situation (presented in the form of minimal pairs) using stringent data analysis (contrasting against a baseline condition) as in our experiment. As C/M with fixed mathematical values may be related to exact magnitude cognition and C/M with variable mathematical values may be linked with approximate quantity conception, future research is needed to investigate the neural correlates of processing C/M with variable mathematical values to better clarify its underlying cognitive mechanism.

We speculated that another reason why Cui et al. (2013) could not find the IPS more activated for classifiers than tool nouns was because that they did not differentiate numerical and non-numerical C/M. Nonetheless, our results of contrast analyses between numerical $C + M_1$ and non-numerical M_3 did not reveal any significant activation, suggesting that processing these two types of C/M involved similar neural activities. In our experiment, participants had to read three nominal phrases and judge which one of the two phrases was semantically closer to the target phrase. When participants made C/M comparison, they had to represent the quantity information that each C/M carry and then choose the C/M with closer mathematical value to the target C/M. Although M_3s encode non-numerical values, they may be represented as a specific numerical value to be compared in the semantic distance comparison task. For example, when participants had to compare *yi bang gang ding (*one pound of steel nails) and *yi ke gang ding* (one gram of steel nails), it is possible that they represent one pound as 453 g to make the semantic judgment. Therefore, it is likely that due to the nature of the semantic distance comparison task in this study, representing C/M as a numerical value was one of the strategies that participants used. This may explain why we did not observe different brain activations contrasting between numerical $C + M_1$ and non-numerical M_3. Future studies are suggested to adopt other active tasks or a passive viewing paradigm to reexamine the neural correlates of numerical and non-numerical C/M and clarify if the underpinning neural activities are similar regardless of experimental paradigms.

In addition to contrast analyses, we conducted conjunction analyses. First, we showed that processing C/M and processing tool nouns commonly induced higher activations in the IOC (including FFG), bilateral IFG (especially in the left hemisphere), left SFG, left MFG (orbital part), and left insula. These regions have been found to engage in phonological and semantic processing in Chinese words (Booth et al., 2006).

Second, the conjunction analysis of number processing (C/M comparison of numerical $C + M_1$, C/M comparison of non-numerical M_3, numbers, dots, and number words) showed higher activation in the IOC including the FFG, bilateral SPL, bilateral IPL, bilateral IFG, right MFG, bilateral SFG, and bilateral insulae. Replicating previous studies, the bilateral IPS were more activated for representation of numerical magnitude regardless of notations (Dehaene et al., 2003; Nieder & Dehaene, 2009). Our findings were also consistent with the recent meta-analysis of number processing that reported the bilateral IPL, left SPL, and the right SFG activated for both symbolic and non-symbolic number processing (Sokolowski et al., 2017).

Third, the conjunction analysis of semantic processing (two noun comparison conditions and the tool noun condition) showed higher activation in the bilateral occipital cortices including the FFG, bilateral SPL, bilateral IFG (especially the left hemisphere), left SFG, and bilateral MFG, which was consistent with previous findings that conceptual representation engaged a distributed neural network in the brain (Cappa, 2012; Price, 2012). Crucially, the left IFG has been shown to activate more naming tools than naming animals while participants engaged in viewing and naming these items (Martin, Wiggs, Ungerleider, & Haxby, 1996).

It is worth discussing the role that the SPL play in number processing and semantic processing. Cui et al. (2013) reported that the angular gyrus, which locates in the SPL, commonly activated for classifiers, tool nouns, numbers, and dot arrays. Replicating the finding by Cui et al. (2013), the angular gyrus was found more activated for both number processing and semantic processing in this study. This suggests that the angular gyrus did not exclusively engage in number processing. However, the activation in the SPL for number processing (18,086 voxels) was a larger cluster than the one elicited by semantic processing (14,504 voxels). In particular, we found that the anterior part of the bilateral IPL, overlapping with the IPS, specifically activated for number processing than semantic processing.

Combining the literature and the findings in this study, we concluded that, linguistically, C/Ms not only highlight nouns with semantic attributes but also denote quantity with a mathematical value. This suggests that the linguistic system of C/M interactes with categorization and magnitude cognition. Moreover, our finding that processing C/Ms with fixed mathematical values elicit higher activations in frontal and parietal regions that have been shown to engage in numerical processing partially supported the mathematical theory of C/M, which suggests that C/Ms encode mathematical values (Her, 2012a). We suggest future studies continue to further investigate the number processing of C/M with variable mathematical values and the multiplication function of C/M to examine the theory more thoroughly. Lastly, our results of conjunction analysis of number processing verified that the IPS represents numerical magnitude independent of notations by providing neural evidence of quantity processing of C/Ms.

Statement of significance to the neurobiology of language

Linguistically, classifiers not only highlight inherent semantic attributes but also denote quantity with a mathematical value. This suggests that numeral classifiers are associated with categorization and magnitude cognition. Our results verified that the intraparietal sulcus represents numerical magnitude independent of notations by providing neural evidence of quantity processing of classifiers.

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Author contributions

O.-S.H. and N.-S.Y. conceived the study. O.-S.H., Y.-C.C., and N.-S.Y designed the study. O.-S. H. and Y.-C.C. developed stimuli and Y.-C. C. collected and analyzed the data. O.-S.H. Y.-C. C. and N.-S.Y. interpreted the data. Y.-C.C. and O.-S.H. wrote the paper.

Appendix A and B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.bandl.2017.10.007.

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