Title: 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 lobule (IPL), middle frontal gyrus (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 ofmagnitude cognition. Furthermore, the results suggest that the IPS represents magnitude independent of notations.

Key words: number processing, numeral classifiers, functional MRI, intraparietal sulcus

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.

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 3 C magazine '3 magazines'	*san xiang zazhi* 3 M-box magazine '3 boxes of magazines'
三 個 蘋果	三 公斤 蘋果
san ge pingguo 3 C apple '3 apples'	*san gongjin pingguo* 3 M-kilo apple '3 kilos of apples'

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; Hsieh, 2008; Her 2012b), 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 iff 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.

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

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 et al., 1998; McCloskey, 1992) or notation-specific (e.g., Cohen-Kadosh et al., 2007).

Neuropsychological studies (e.g., Butterworth et al., 2001; Cappelletti et al., 2006; Cipolotti et al., 1995) and neuroimaging studies (e.g., Cui et al., 2013; Wei et al., 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 et al., 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 those 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 plays 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.

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[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. 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.

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 suggest 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 (Tai & Wang, 1990; Her, 2012a). 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).

Therefore, we conducted a second experiment and controlled the semantic attributes of C/M by using minimal pairs as stimuli (Her et al., 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; Dehaene et al., 2003), we expected to find greater activations in the IPS for processing C/Ms than tool nouns by adopting our modified paradigm.

Method

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.

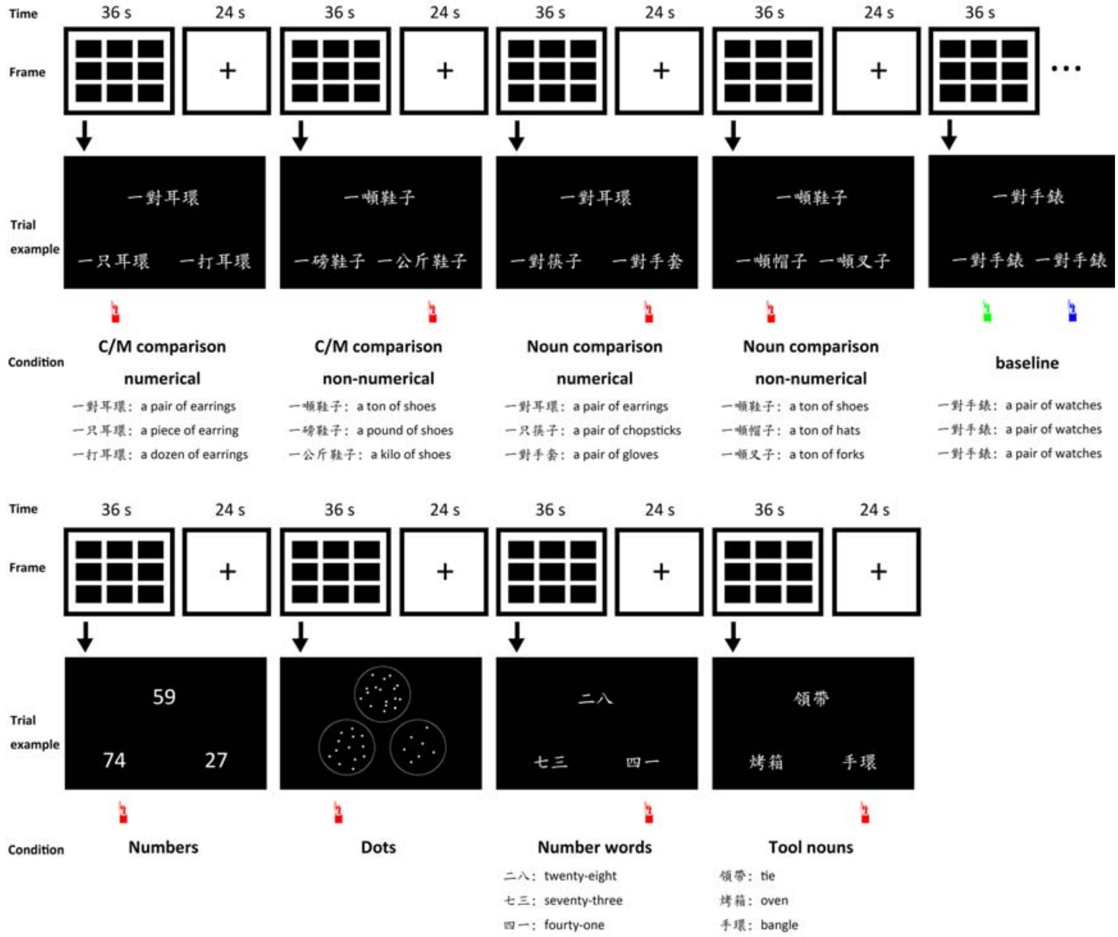
Stimuli and Materials

We conducted a within-subject design and manipulated two variables. The two independent variables were comparison (C/Ms vs. tool noun) 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 Figure 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/M 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).

***Figure* 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.



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.

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 (Figure 1).

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 × 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 × 1 × 1 mm^3) was acquired using a standard MPRAGE sequence, with a 7° flip angle, 2530 ms TR, 3.3 ms TE and 1,100 ms inversion time (TI).

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. 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.

Results

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).

Contrast analyses

Figure 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 lobule (IPL) including the IPS, right superior frontal gyrus (SFG), bilateral middle frontal gyrus (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.

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

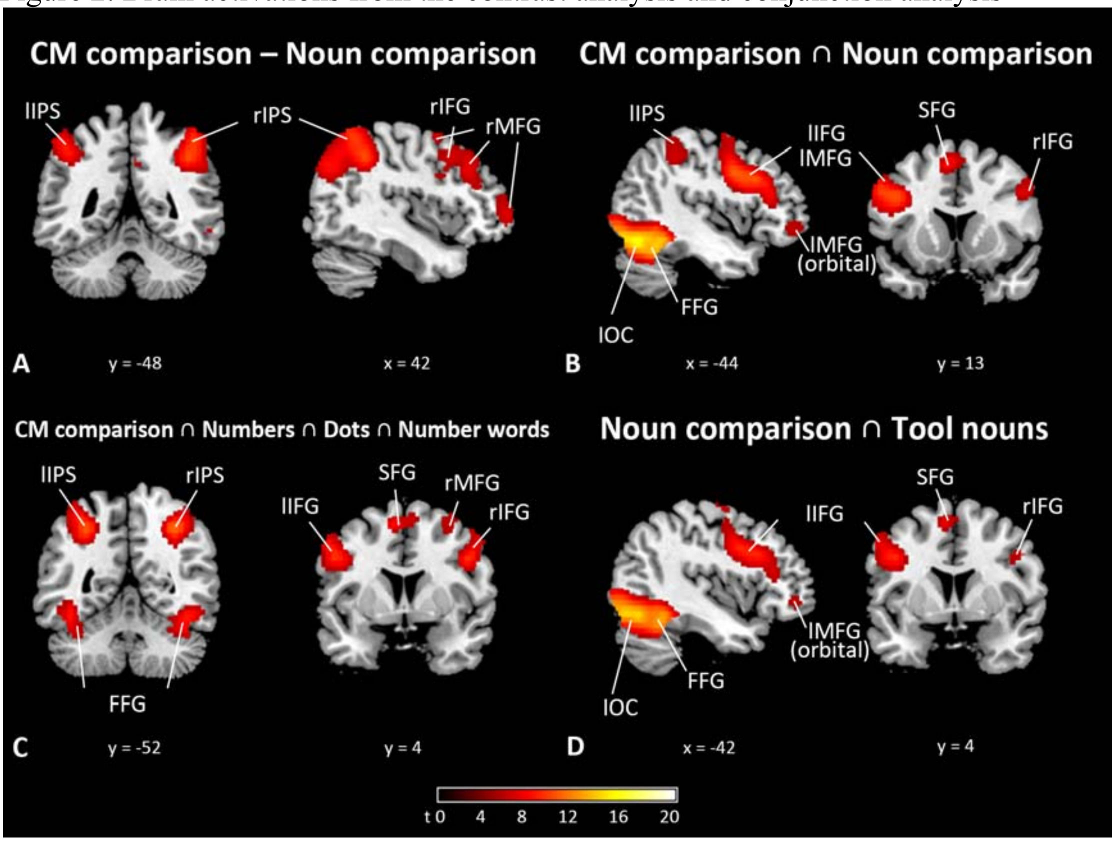


Table 3

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						

Conjunction analyses

Conjunction analysis of the four main conditions (processing C/M or tool nouns in classifier phrases with either a numerical C+M_1 or a non-numerical M_3) showed activation in the bilateral inferior occipital cortex (IOC) including the fusiform gyrus (FFG), bilateral inferior frontal gyrus (IFG, especially in the left hemisphere), left SFG, left MFG (orbital part), and left insula (see Figure 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 lobule (SPL), bilateral inferior parietal lobule, bilateral IFG, right MFG, bilateral SFG, and bilateral insula (see Figure 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 cortex including the FFG, bilateral superior parietal lobule, bilateral IFG (mostly in the left hemisphere), left SFG, and bilateral MFG (see Figure 2D and Table 4).

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 x	y	z	t-Value	Cluster size
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	18086
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

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 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, Piazza, Pinel, & Cohen, 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 was found activated during number proceeising 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 grams 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 insula. 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 cortex 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 et al, 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 (18086 voxels) was a larger cluster than the one elicited by semantic processing (14504 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 withcategorization 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.

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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.

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Appendix A

Experimental Stimuli used in the current study

Condition	Target	Answer	Distractor	CM/ Tool noun
C/M comparison, numerical	一打 *yi da* one dozen of	一對 *yi dui* one pair of	一根 *yi gen* one C (something long-shaped)	牙刷 *yashua* toothbrush
	一打 *yi da* one dozen of	一對 *yi dui* one pair of	一只 *yi zhi* one piece of	手鍊 *shoulian* bracelet
	一雙 *yi shuang* one pair of	一對 *yi dui* one pair of	一只 *yi zhi* one piece of	鐲子 *zhuozi* bangle
	一對 *yi dui* one pair of	一根 *yi gen* one C (something long-shaped)	一打 *yi da* one dozen of	粉筆 *fenbi* chalk
	一副 *yi fu* one pair of	一枝 *yi zhi* one C (something long-shaped)	一打 *yi da* one dozen of	鋼筆 *gangbi* fountain pen
	一對 *yi dui* one pair of	一只 *yi zhi* one piece of	一打 *yi da* one dozen of	湯匙 *tangchi* spoon
	一根 *yi gen* one C (something long-shaped)	一只 *yi zhi* one piece of	一對 *yi dui* one pair of	釣竿 *dioagan* fishing rod
	一根 *yi gen* one C (something long-shaped)	一對 *yi dui* one pair of	一打 *yi da* one dozen of	雨傘 *yusan* umbrella
	一只 *yi zhi* one piece of	一副 *yi fu* one pair of	一打 *yi da* one dozen of	蠟燭 *lazhu* candle
	一雙 *yi shuang* one pair of	一對 *yi dui* one pair of	一只 *yi zhi* one piece of	手錶 *shoubiao* watch
	一打 *yi da* one dozen of	一副 *yi fu* one pair of	一根 *yi gen* one C (something long-shaped)	牙籤 *yaqian* toothpick
	一副 *yi fu* one pair of	一對 *yi dui* one set of	一只 *yi zhi* one piece of	耳環 *erhuan* earring

	一對 *yi dui* one pair of	一枝 *yi zhi* one C (something long-shaped)	一打 *yi da* one dozen of	鉛筆 *qianbi* pencil
	一雙 *yi shuang* one pair of	一只 *yi zhi* one piece of	一打 *yi da* one dozen of	手套 *shoutao* glove
	一副 *yi fu* one pair of	一根 *yi gen* one C (something long-shaped)	一打 *yi da* one dozen of	眉筆 *meibi* eyebrow pencil
	一雙 *yi shuang* one pair of	一對 *yi dui* one pair of	一打 *yi da* one dozen of	布偶 *buou* rag doll
	一枝 *yi zhi* one C (something long-shaped)	一雙 *yi shuang* one pair of	一打 *yi da* one dozen of	叉子 *chazi* fork
	一枝 *yi zhi* one C (something long-shaped)	一對 *yi dui* one pair of	一打 *yi da* one dozen of	圓規 *yuangui* compasses
	一打 *yi da* one dozen of	一副 *yi fu* one pair of	一枝 *yi zhi* one C (something long-shaped)	長劍 *changjian* sword
	一打 *yi da* one dozen of	一雙 *yi shuang* one pair of	一枝 *yi zhi* one C (something long-shaped)	拐杖 *guaizhang* cane
	一副 *yi fu* one pair of	一雙 *yi shuang* one pair of	一只 *yi zhi* one piece of	腳鍊 *jiaolian* anklet
	一副 *yi fu* one pair of	一只 *yi zhi* one piece of	一打 *yi da* one dozen of	手錶 *shoubiao* watch
	一雙 *yi shuang* one pair of	一枝 *yi zhi* one C (something long-shaped)	一打 *yi da* one dozen of	竹筷 *zhukuai* bamboo chopsticks
	一雙 *yi shuang* one pair of	一根 *yi gen* one C (something long-shaped)	一打 *yi da* one dozen of	毛筆 *maobi* writing brush
	一枝 *yi zhi* one C (something long-shaped)	一根 *yi gen* one C (something long-shaped)	一雙 *yi shuang* one pair of	筷子 *kuaizi* chopsticks

	一根 *yi gen* one C (something long-shaped)	一雙 *yi shuang* one pair of	一打 *yi da* one dozen of	吸管 *xiguan* straw
	一只 *yi zhi* one piece of	一雙 *yi shuang* one pair of	一打 *yi da* one dozen of	襪子 *wazi* sock
C/M comparison, non-numerical	一噸 *yi dun* one ton	一磅 *yi bang* one pound	一克 *yi ke* one gram	鋼釘 *gangding* steel nails
	一公里 *yi gongli* one kilometer	一寸 *yi cun* one cun (=1/3 decimetre)	一公分 *yi gongfen* one centimeter	電線 *dianxian* wire
	一磅 *yi bang* one pound	一兩 *yi liang* one tael	一克 *yi ke* one gram	鈕扣 *niukou* button
	一兩 *yi liang* one tael	一克 *yi ke* one gram	一磅 *yi bang* one pound	鋼絲 *gangsi* steel wire
	一磅 *yi bang* one pound	一兩 *yi liang* one tael	一公斤 *yi gongjin* one kilo	扣子 *kouzi* button
	一寸 *yi cun* one cun (=1/3 decimetre)	一公分 *yi gongfen* one centimeter	一公里 *yi gongli* one kilometer	緞帶 *duandai* ribbon
	一公斤 *yi gongjin* one kilo	一磅 *yi bang* one pound	一噸 *yi dun* one ton	釘子 *dingzi* nail
	一公分 *yi gongfen* one centimeter	一寸 *yi cun* one cun (=1/3 decimetre)	一公里 *yi gongli* one kilometer	管線 *guanxian* pipeline
	一克 *yi ke* one gram	一兩 *yi liang* one tael	一公斤 *yi gongjin* one kilo	別針 *biezhen* pin
	一公里 *yi gongli* one kilometer	一公尺 *yi gongchi* one meter	一公分 *yi gongfen* one centimeter	水管 *shuiguan* water pipe
	一公里 *yi gongli* one kilometer	一公尺 *yi gongchi* one meter	一寸 *yi cun* one cun (=1/3 decimetre)	鋼絲 *gangsi* steel wire
	一公斤 *yi gongjin* one kilo	一磅 *yi bang* one pound	一克 *yi ke* one gram	鉛筆 *qianbi* pencil

	一兩 *yi liang* one tael	一克 *yi ke* one gram	一噸 *yi dun* one ton	圖釘 *tuding* push pin
	一寸 *yi cun* one cun (=1/3 decimetre)	一公分 *yi gongfen* one centimeter	一公尺 *yi gongchi* one meter	鐵絲 *tiesi* iron wire
	一寸 *yi cun* one cun (=1/3 decimetre)	一公分 *yi gongfen* one centimeter	一公尺 *yi gongchi* one meter	銅線 *tongxian* copper wire
	一磅 *yi bang* one pound	一公斤 *yi gongjin* one kilo	一噸 *yi dun* one ton	引擎 *yinqing* engine
	一兩 *yi liang* one tael	一磅 *yi bang* one pound	一噸 *yi dun* one ton	鐲子 *zhuozi* bangle
	一公分 *yi gongfen* one centimeter	一公尺 *yi gongchi* one meter	一公里 *yi gongli* one kilometer	電纜 *dianlan* cable
	一公里 *yi gongli* one kilometer	一公尺 *yi gongchi* one meter	一寸 *yi cun* one cun (=1/3 decimetre)	電線 *dianxian* wire
	一公斤 *yi gongjin* one kilo	一兩 *yi liang* one tael	一克 *yi ke* one gram	耳環 *erhuan* earring
	一噸 *yi dun* one ton	一公斤 *yi gongjin* one kilo	一克 *yi ke* one gram	粉筆 *fenbi* chalk
	一公斤 *yi gongjin* one kilo	一兩 *yi liang* one tael	一噸 *yi dun* one ton	子彈 *zidan* bullet
	一公尺 *yi gongchi* one meter	一寸 *yi cun* one cun (=1/3 decimetre)	一公里 *yi gongli* one kilometer	鐵軌 *tiegui* rail
	一磅 *yi bang* one pound	一克 *yi ke* one gram	一噸 *yi dun* one ton	牙刷 *yashua* toothbrush
	一克 *yi ke* one gram	一兩 *yi liang* one tael	一磅 *yi bang* one pound	手鍊 *sho lian* bracelet
	一寸 *yi cun* one cun (=1/3 decimetre)	一公尺 *yi gongchi* one meter	一公里 *yi gongli* one kilometer	纜繩 *lansheng* canble

	一克 *yi ke* one gram	一磅 *yi bang* one pound	一噸 *yi dun* one ton	螺帽 *luomao* blind nut
Tool noun comparison, numerical	牙刷 *yashua* toothbrush	眉筆 *meibi* eyebrow pencil	螺帽 *luomao* blind nut	一副 *yi fu* one pair of
	湯匙 *tangchi* spoon	筷子 *kuaizi* chopstick	引擎 *yinqing* engine	一打 *yi da* one dozen of
	鋼絲 *gangsi* steel wire	銅線 *tongxian* copper wire	牙籤 *yaqian* toothpick	一根 *yi gen* one C (something long-shaped)
	耳環 *erhuan* earring	鐲子 *zhuozi* bangle	拐杖 *guaizhang* cane	一雙 *yi shuang* one pair of
	吸管 *xiguan* straw	湯匙 *tangchi* spoon	扣子 *kouzi* button	一只 *yi zhi* one piece of
	圓規 *yuangui* compasses	鉛筆 *qianbi* pencil	鈕扣 *niukou* button	一對 *yi dui* one pair of
	雨傘 *yusan* umbrella	牙刷 *yashua* toothbrush	管線 *guanxian* pipeline	一枝 *yi zhi* one C (something long-shaped)
	緞帶 *duandai* ribbon	鈕扣 *niukou* button	叉子 *chazi* fork	一副 *yi fu* one pair of
	扣子 *ko zi* button	手套 *shoutao* glove	鐵絲 *tiesi* iron wire	一打 *yi da* one dozen of
	子彈 *zidan* bullet	長劍 *changjian* sword	鐲子 *zhuozi* bangle	一對 *yi dui* one pair of
	竹筷 *zhukuai* bamboo chopsticks	叉子 *chazi* fork	毛筆 *maobi* writing brush	一枝 *yi zhi* one C (something long-shaped)
	鐵軌 *tiegui* rail	電纜 *dianlan* cable	腳鍊 *jiaolian* anklet	一副 *yi fu* one pair of
	銅線 *tongxian* copper wire	水管 *shuiguan* water pipe	緞帶 *duandai* ribbon	一打 *yi da* one dozen of

	鋼釘 *gangding* steel nails	鐵絲 *tiesi* iron wire	雨傘 *yusan* umbrella	一根 *yi gen* one C (something long-shaped)
	手鍊 *shoulian* bracelet	襪子 *wazi* sock	螺帽 *luomao* blind nut	一雙 *yi shuang* one pair of
	別針 *biezhen* pin	手套 *shoutao* glove	釣竿 *dioagan* fishing rod	一只 *yi zhi* one piece of
	手槍 *shouqiang* pistol	子彈 *zidan* bullet	蠟燭 *lazhu* candle	一對 *yi dui* one pair of
	電纜 *dianlan* cable	鋼釘 *gangding* steel nails	蠟燭 *lazhu* candle	一枝 *yi zhi* one C (something long-shaped)
	襪子 *wazi* sock	手套 *shoutao* glove	吸管 *xiguan* straw	一雙 *yi shuang* one pair of
	手錶 *shoubiao* watch	耳環 *erhuan* earring	圓規 *yuangui* compasses	一只 *yi zhi* one piece of
	螺帽 *luomao* blind nut	釘子 *dingzi* nail	鋼筆 *gangbi* fountain pen	一對 *yi dui* one pair of
	牙籤 *yaqian* toothpick	竹筷 *zhukuai* bamboo chopsticks	鉛筆 *qianbi* pencil	一枝 *yi zhi* one C (something long-shaped)
	球拍 *qiupai* racket	釣竿 *dioagan* fishing rod	手鍊 *shoulian* bracelet	一副 *yi fu* one pair of
	拐杖 *guaizhang* cane	雨傘 *yusan* umbrella	手槍 *shouqiang* pistol	一打 *yi da* one dozen of
	水管 *shuiguan* water pipe	電線 *dianxian* wire	粉筆 *fenbi* chalk	一根 *yi gen* one C (something long-shaped)
	管線 *guanxian* pipeline	纜繩 *lansheng* cable	圖釘 *tuding* push pin	一根 *yi gen* one C (something

				long-shaped)
	鋼筆 *gangbi* fountain pen	圖釘 *tuding* push pin	長劍 *changjian* sword	一只 *yi zhi* one piece of
Tool noun comparison, non-numerical	鐲子 *zhuozi* bangle	手鍊 *shoulian* bracelet	圖釘 *tuding* push pin	一兩 *yi liang* one tael
	引擎 *yinqing* engine	螺帽 *luomao* blind nut	竹筷 *zhukuai* bamboo chopsticks	一噸 *yi dun* one ton
	鐵絲 *tiesi* iron wire	釘子 *dingzi* nail	蠟燭 *lazhu* candle	一公分 *yi gongfen* one centimeter
	筷子 *kuaizi* chopsticks	吸管 *xiguan* straw	鈕扣 *niukou* button	一兩 *yi liang* one tael
	襪子 *wazi* sock	手錶 *shoubiao* watch	釣竿 *dioagan* fishing rod	一噸 *yi dun* one ton
	鈕扣 *niukou* button	別針 *biezhen* pin	鋼絲 *gangsi* steel wire	一寸 *yi cun* one cun (=1/3 decimetre)
	銅線 *tongxian* copper wire	鐵絲 *tiesi* iron wire	鈕扣 *niukou* button	一兩 *yi liang* one tael
	水管 *shuiguan* water pipe	電纜 *dianlan* cable	扣子 *kouzi* button	一噸 *yi dun* one ton
	鐵軌 *tiegui* rail	水管 *shuiguan* water pipe	球拍 *qiupai* racket	一公尺 *yi gongchi* one meter
	別針 *biezhen* pin	扣子 *kouzi* button	粉筆 *fenbi* chalk	一克 *yi ke* one gram
	牙籤 *yaqian* toothpick	湯匙 *tangchi* spoon	眉筆 *meibi* eyebrow pencil	一寸 *yi cun* one cun (=1/3 decimetre)
	電線 *dianxian* wire	纜繩 *lansheng* canble	長劍 *changjian* sword	一公尺 *yi gongchi* one meter
	毛筆 *maobi* writing brush	圖釘 *tuding* push pin	耳環 *erhuan* earring	一克 *yi ke* one gram
	鉛筆	圓規	牙刷	一寸

	qianbi pencil	*yuangui* compasses	*yashua* toothbrush	*yi cun* one cun (=1/3 decimetre)
	電纜 *dianlan* cable	管線 *guanxian* pipeline	拐杖 *guaizhang* cane	一公尺 *yi gongchi* one meter
	螺帽 *luomao* blind nut	鋼釘 *gangding* steel nails	別針 *biezhen* pin	一克 *yi ke* one gram
	腳鍊 *jiaolian* anklet	鐲子 *zhuozi* bangle	牙籤 *yaqian* toothpick	一寸 *yi cun* one cun (=1/3 decimetre)
	鋼絲 *gangsi* steel wire	纜繩 *lansheng* cable	緞帶 *duandai* ribbon	一公尺 *yi gongchi* one meter
	子彈 *zidan* bullet	手槍 *shouqiang* pistol	襪子 *wazi* sock	一磅 *yi bang* one pound
	鋼釘 *gangding* steel nails	銅線 *tongxian* copper wire	緞帶 *duandai* ribbon	一公分 *yi gongfen* one centimeter
	圓規 *yuangui* compasses	鋼筆 *gangbi* fountain pen	雨傘 *yusan* umbrella	一公斤 *yi gongjin* one kilo
	叉子 *chazi* fork	牙籤 *yaqian* toothpick	手套 *shoutao* glove	一磅 *yi bang* one pound
	耳環 *erhuan* earring	緞帶 *duandai* ribbon	吸管 *xiguan* straw	一公分 *yi gongfen* one centimeter
	竹筷 *zhukuai* bamboo chopsticks	叉子 *chazi* fork	雨傘 *yusan* umbrella	一公斤 *yi gongjin* one kilo
	湯匙 *tangchi* spoon	筷子 *kuaizi* chopsticks	毛筆 *maobi* writing brush	一磅 *yi bang* one pound
	電線 *dianxian* wire	鐵絲 *tiesi* iron wire	粉筆 *fenbi* chalk	一公分 *yi gongfen* one centimeter
	手錶 *shoubiao* watch	腳鍊 *jiaolian* anklet	鋼筆 *gangbi* fountain pen	一公斤 *yi gongjin* one kilo
Baseline	一枝粉筆 *yi zhi fenbi* one C chalk	一枝粉筆 *yi zhi fenbi* one C chalk	一枝粉筆 *yi zhi fenbi* one C chalk	
	一副筷子	一副筷子	一副筷子	

	yi fu kuaizi one pair of chopsticks	*yi fu kuaizi* one pair of chopsticks	*yi fu kuaizi* one pair of chopsticks	
	一打毛筆 *yi da maobi* one dozen of writing brushes	一打毛筆 *yi da maobi* one dozen of writing brushes	一打毛筆 *yi da maobi* one dozen of writing brushes	
	一磅牙刷 *yi bang yashua* one pound of toothbrushes	一磅牙刷 *yi bang yashua* one pound of toothbrushes	一磅牙刷 *yi bang yashua* one pound of toothbrushes	
	一寸吸管 *yi cun xiguan* one cun of straw (=1/3 decimetre)	一寸吸管 *yi cun xiguan* one cun of straw (=1/3 decimetre)	一寸吸管 *yi cun xiguan* one cun of straw (=1/3 decimetre)	
	一枝拐杖 *yi zhi guaizhang* one C cane	一枝拐杖 *yi zhi guaizhang* one C cane	一枝拐杖 *yi zhi guaizhang* one C cane	
	一副管線 *yi fu guanxian* one pair of pipelines	一副管線 *yi fu guanxian* one pair of pipelines	一副管線 *yi fu guanxian* one pair of pipelines	
	一克扣子 *yi ke kouzi* one gram of button	一克扣子 *yi ke kouzi* one gram of button	一克扣子 *yi ke kouzi* one gram of button	
	一寸鉛筆 *yi cun qianbi* one cun of pencil	一寸鉛筆 *yi cun qianbi* one cun of pencil	一寸鉛筆 *yi cun qianbi* one cun of pencil	
	一只球拍 *yi zhi qiu pai* one piece of racket	一只球拍 *yi zhi qiu pai* one piece of racket	一只球拍 *yi zhi qiu pai* one piece of racket	
	一對手錶 *yi dui shoubiao* one pair of watches	一對手錶 *yi dui shoubiao* one pair of watches	一對手錶 *yi dui shoubiao* one pair of watches	
	一克圖釘 *yi ke tuding* one gram of push pin	一克圖釘 *yi ke tuding* one gram of push pin	一克圖釘 *yi ke tuding* one gram of push pin	
	一公斤釣竿 *yi gongjin dioagan* one kilo of fishing rod	一公斤釣竿 *yi gongjin dioagan* one kilo of fishing rod	一公斤釣竿 *yi gongjin dioagan* one kilo of fishing rod	
	一公尺長劍 *yi gongchi changjian* one meter of sword	一公尺長劍 *yi gongchi changjian* one meter of sword	一公尺長劍 *yi gongchi changjian* one meter of sword	

	一只圓規 *yi zhi yuangui* one pair of compasses	一只圓規 *yi zhi yuangui* one pair of compasses	一只圓規 *yi zhi yuangui* one pair of compasses	
	一對腳鍊 *yi dui jiaolian* one pair of anklets	一對腳鍊 *yi dui jiaolian* one pair of anklets	一對腳鍊 *yi dui jiaolian* one pair of anklets	
	一兩子彈 *yi liang zidan* one tael of bullets	一兩子彈 *yi liang zidan* one tael of bullets	一兩子彈 *yi liang zidan* one tael of bullets	
	一公尺鋼絲 *yi gongchi gangsi* one meter of steel wire	一公尺鋼絲 *yi gongchi gangsi* one meter of steel wire	一公尺鋼絲 *yi gongchi gangsi* one meter of steel wire	
	一根釘子 *yi gen dingzi* one nail	一根釘子 *yi gen dingzi* one nail	一根釘子 *yi gen dingzi* one nail	
	一雙眉筆 *yi shuang meibi* one pair of eyebrow pencils	一雙眉筆 *yi shuang meibi* one pair of eyebrow pencils	一雙眉筆 *yi shuang meibi* one pair of eyebrow pencils	
	一兩蠟燭 *yi liang lazhu* one tael of candles	一兩蠟燭 *yi liang lazhu* one tael of candles	一兩蠟燭 *yi liang lazhu* one tael of candles	
	一噸手槍 *yi dun shouqiang* one ton of pistols	一噸手槍 *yi dun shouqiang* one ton of pistols	一噸手槍 *yi dun shouqiang* one ton of pistols	
	一公里鐵軌 *yi gongli tiegui* one kilometer of rails	一公里鐵軌 *yi gongli tiegui* one kilometer of rails	一公里鐵軌 *yi gongli tiegui* one kilometer of rails	
	一根纜繩 *yi gen lansheng* one cable	一根纜繩 *yi gen lansheng* one cable	一根纜繩 *yi gen lansheng* one cable	
	一雙手鍊 *yi shuang shoulian* one pair of bracelets	一雙手鍊 *yi shuang shoulian* one pair of bracelets	一雙手鍊 *yi shuang shoulian* one pair of bracelets	
	一噸引擎 *yi dun yinqing* one ton of engines	一噸引擎 *yi dun yinqing* one ton of engines	一噸引擎 *yi dun yinqing* one ton of engines	
	一公里電線 *yi gongli dianxian* one kilometer of wire	一公里電線 *yi gongli dianxian* one kilometer of wire	一公里電線 *yi gongli dianxian* one kilometer of wire	
Numbers	26	17	15	
	62	58	56	

	82	77	73	
	32	28	39	
	53	49	59	
	83	88	77	
	31	37	39	
	44	52	55	
	83	85	89	
	35	33	32	
	51	44	41	
	93	87	84	
	24	28	18	
	66	67	63	
	71	68	79	
	23	24	27	
	57	62	63	
	72	81	83	
	17	11	10	
	48	45	41	
	74	73	72	
	16	13	24	
	47	49	41	
	92	89	96	
	10	14	15	
	64	67	70	
	90	97	98	
Dots	17	13	7	
	62	54	40	
	74	67	49	
	24	19	36	
	53	56	38	
	92	99	67	
	23	26	36	
	44	46	59	
	80	83	99	
	35	32	20	
	48	47	34	
	82	76	56	
	16	18	10	
	66	60	89	
	71	81	47	
	10	15	21	

	57	58	71	
	72	75	97	
	26	21	12	
	51	49	37	
	93	84	66	
	32	33	19	
	47	43	61	
	80	78	99	
	31	35	43	
	64	70	86	
	73	77	98	
Number words	二七 *er-qi* twenty-seven	十八 *shi-ba* eighteen	十六 *shi-liu* sixteen	
	五二 *wu-er* fifty-two	四五 *si-wu* forty-five	四二 *si-er* forty-two	
	九四 *jiu-si* ninety-four	八八 *ba-ba* eighty-eight	八五 *ba-wu* eighty-five	
	二五 *er-wu* twenty-five	二九 *er-jiu* twenty-nine	十九 *shi-jiu* nineteen	
	四八 *si-ba* forty-eight	五十 *wu-shi* fifty	四二 *si-er* forty-two	
	八四 *ba-si* eighty-four	八九 *ba-jiu* eighty-nine	七八 *qi-ba* seventy-eight	
	二四 *er-si* twenty-four	二五 *er-wu* twenty-five	二八 *er-ba* twenty-eight	
	六五 *liu-wu* sixty-five	六八 *liu-ba* sixty-eight	七一 *qi-yi* seventy-one	
	九一 *jiu-yi* ninety-one	九八 *jiu-ba* ninety-eight	九九 *jiu-jiu* ninety-nine	
	四九 *si-jiu* forty-nine	四六 *si-liu* forty-six	四二 *si-er* forty-two	
	三六 *san-liu* thirty-six	三四 *san-si* thirty-four	三三 *san-san* thirty-three	
	八三	七八	七四	

	ba-san eighty-three	*qi-ba* seventy-eight	*qi-si* seventy-four	
	十七 *shi-qi* seventeen	十四 *shi-si* fourteen	二五 *er-wu* twenty-five	
	七二 *qi-er* seventy-two	六九 *liu-jiu* sixty-nine	八十 *ba-shi* eighty	
	六七 *liu-qi* sixty-seven	六八 *liu-ba* sixty-eight	六四 *liu-si* sixty-four	
	四五 *si-wu* forty-five	五三 *wu-san* fifty-three	五六 *wu-liu* fifty-six	
	三二 *san-er* thirty-two	三八 *san-ba* thirty-eight	四十 *si-shi* forty	
	七三 *qi-san* seventy-three	八二 *ba-er* eighty-two	八四 *ba-si* eighty-four	
	十八 *shi ba* eighteen	十二 *shi er* twelve	十一 *shi yi* eleven	
	六三 *liu-san* sixty-three	五九 *wu-jiu* fifty-nine	五七 *wu-qi* fifty-seven	
	七五 *qi-wu* seventy-five	七四 *qi-si* seventy-four	七三 *qi-san* seventy-three	
	三三 *san-san* thirty-three	二九 *er-jiu* twenty-nine	四十 *si-shi* forty	
	五四 *wu-si* fifty-four	五十 *wu-shi* fifty	六十 *liu-shi* sixty	
	九三 *jiu-san* ninety-three	九十 *jiu-shi* ninety	九七 *jiu-qi* ninety-seven	
	十一 *shi-yi* eleven	十五 *shi-wu* fifteen	十六 *shi-liu* sixteen	
	五八 *wu-ba* fifty-eight	六三 *liu-san* sixty-three	六四 *liu-si* sixty-four	
	八四 *ba-si* eighty-four	八六 *ba-liu* eighty-six	九十 *jiu-shi* ninety	

Nouns	毛巾 *ma jin* towel	枕頭 *zhentou* pillow	弓箭 *gongjian* bow and arrow	
	領帶 *lingdai* necktie	手環 *shouhuan* wristband	烤箱 *kaoxiang* oven	
	步槍 *buqiang* rifle	導彈 *daodan* missile	硯台 *yantai* inkstone	
	帽子 *maozi* hat	戒指 *jiezhi* ring	膠帶 *jiaodai* tape	
	茶壺 *chahu* teapot	烤箱 *kaoxiang* oven	枕頭 *zhe tou* pillow	
	茶杯 *chabei* teacup	鍋子 *guozi* pot	網球 *wang qiu* tennis	
	鏡子 *jingzi* mirror	毛巾 *mao jin* towel	步槍 *bu qiang* rifle	
	啞鈴 *yaling* dumbbells	球棒 *qiubang* bat	茶壺 *chahu* teapot	
	枕頭 *zhentou* pillow	口紅 *kouhong* lipstick	球棒 *qiubang* bat	
	鍋子 *guozi* pot	茶杯 *chabei* teacup	啞鈴 *yaling* dumbbells	
	蠟筆 *labi* crayon	膠帶 *jiaodai* tape	鷹架 *yingjia* scaffolding	
	戒指 *jiezhi* ring	裙子 *qunzi* skirt	筆筒 *bitong* pen holder	
	弓箭 *gongjian* bow and arrow	步槍 *buqiang* rifle	手環 *shouhuan* wristband	
	天線 *tianxian* antenna	鷹架 *yingjia* scaffolding	茶杯 *chabei* teacup	
	鷹架 *yingjia* scaffolding	螺絲 *luosi* screw	領帶 *lingdai* necktie	
	烤箱 *kaoxiang*	盤子 *panzi*	帽子 *maozi*	

	oven	plate	hat	
	球棒 *qiubang* bat	網球 *wangqiu* tennis	蠟筆 *labi* crayon	
	膠帶 *jiaodai* tape	硯台 *yantai* inkstone	滑板 *huaban* skateboard	
	網球 *wangqiu* tennis	滑板 *huaban* skateboard	盤子 *panzi* plate	
	螺絲 *luosi* screw	扳手 *banshou* wrench	鏡子 *jingzi* mirror	
	盤子 *panzi* plate	茶壺 *chahu* teapot	天線 *tianxian* antenna	
	滑板 *huaban* skateboard	啞鈴 *yaling* dumbbells	裙子 *qunzi* skirt	
	筆筒 *bitong* pen holder	蠟筆 *labi* crayon	導彈 *daodan* missile	
	硯台 *yantai* inkstone	筆筒 *bitong* pen holder	毛巾 *maojin* towel	
	裙子 *qunzi* skirt	手環 *shouhuan* wristband	扳手 *banshou* wrench	
	口紅 *kouhong* lipstick	鏡子 *jingzi* mirror	鍋子 *guozi* pot	
	扳手 *banshou* wrench	天線 *tianxian* antenna	口紅 *kouhong* lipstick	

(Appendices continue)

Appendix B

The means (standard deviations) of the number of strokes, frequency of C/Ms, and frequency of tool nouns of the four main experimental conditions and the baseline condition. The word frequency (number of occurrence in the database of Modern Mandarin Corpus) was obtained from the Digital Resources Center for Global Chinese Language Teaching and Learning (Cheng et al., 2005).

	C/M comparison, numerical	C/M comparison, non-numerical	Tool noun comparison, numerical	Tool noun comparison, non-numerical	Baseline
Number of strokes	95.44 (3.29)	104.96 (4.16)	100.56 (4.06)	99.22 (3.07)	100.00 (5.13)
Frequency of C/Ms	153.36 (14.26)	215.43 (23.76)	171.22 (13.78)	224.78 (24.54)	210.37 (21.24)
Frequency of tool nouns	19.00 (1.58)	16.67 (2.06)	18.94 (2.15)	16.91 (1.96)	24.11 (2.62)