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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.