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The role of inferior frontal gyrus in processing Chinese classifiers

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ABSTRACT

The Chinese classifier system classifies nouns and builds a relation between classifiers and their corresponding nouns. This functional magnetic resonance imaging (fMRI) study examined brain activation of Chinese classifiers during reading comprehension. Thirty-four participants read and performed semantic congruency judgments on congruent, inside-classifier (IC) violated, and outside-classifier (OC) violated sentences. The IC and OC violations were created by changing the correct classifier to an inappropriate classifier and a non-classifier, respectively. The comparison of the IC violation vs. the congruent condition produced greater activation in the mid-ventral region (BA 45) of the left inferior frontal gyrus (IFG), suggesting an increased demand on semantic processing. Contrasting different subtypes of IC violation produced greater activation in the right IFG (BAs 45 and 47), indicating that processing mass/count classifiers involves distinct brain activations. The OC violation produced greater activation in the left IFG (BAs 45 and 44), suggesting both semantic and syntactic processing. These results indicate that different parts of the IFG contribute to syntactic and semantic processing of classifier phrases in reading Chinese for comprehension.

1. Introduction

The ability to process language, and more specifically, the ability to comprehend text structures in reading, has been described as one of the most remarkable skills that are unique to humans (Fitch, Hauser, & Chomsky, 2002). Thus, it is important to understand the processes and neural correlates underpinning reading comprehension. Among various processes involved in reading, semantic processing and related neural pathways have attracted much attention in past studies. Indeed, semantic processing has been found to be mainly associated with activations in the left posterior superior temporal gyrus (Brauer & Friederici, 2007; Constable et al., 2004), the left posterior middle temporal gyrus (Davis & Johnsrude, 2003; Rodd, Davis, & Johnsrude, 2005), and the ventral regions (BA 45, 47) of the left inferior frontal gyrus (Mestres-Missé, Càmara, Rodriguez-Fornells, Rotte, & Münte, 2008; Stringaris, Medford, Giampietro, Brammer, & David, 2007).

The aforementioned evidence on neural correlates of semantic processes during reading comprehension mainly comes from English and other European languages. However, there is neural and behavioral evidence to show that both common and distinct processes are involved in processing European and non-European languages (e.g., Chen & Juola, 1982; Cheung, Chen, Lai, Wong, & Hills, 2001; Cutler & Otake, 1994; Gandour et al., 2002; Jiang & Zhou, 2009; Schirmer, Tang, Penney, Gunter, & Chen, 2005; Ye, Luo, Friederici, & Zhou, 2006). For example, in European languages, semantically incongruent words usually elicit an N400 effect at 400–500 ms after word onset, relative to congruent words, and this effect reaches its maximum at central/centro-parietal sites (e.g., Friederici, Pfeifer, & Hahne, 1993; Hagoort & Brown, 2000; Holcomb & Neville, 1990). In Cantonese, a southern Chinese dialect, Schirmer et al. also found that varying semantic congruency produced an N400-like negativity. However, this negativity, with a more frontal distribution and a shorter latency at 300 ms following the onset of a target word, mismatched in both scalp topography and latency from results in European languages, suggesting that language-specific properties (e.g., the use of tone and the degree of homophony) modulate the neuronal structures involved in lexical processing. Thus, the understanding of language processing will be incomplete without considering how it is done in distinctively different languages.

Recently, several studies have used functional magnetic resonance imaging (fMRI) to explore the neural substrates of semantic and syntactic processing in reading Chinese, a very popular Asian tone language with a logographic script. For example, using the violation paradigm developed by Chen (1992, 1999), Wang et al. (2008) created three conditions: the semantic violation (SEM), the semantic and syntactic violation (SEM + SYN), and the congruent

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condition (CON). The two violation conditions were constructed through substituting the target word in a congruent sentence (e.g., we bake "bread" in an oven) with a semantically anomalous but syntactically appropriate word (e.g., "bank") or a semantically and syntactically inappropriate word ("remove"). The results showed that, when compared with the SEM condition, the SEM + SYN condition produced greater activation in the dorsal region (BA 44) of the left inferior frontal gyrus (IFG), suggesting that this region plays a role in syntactic processing independent of semantic processing in Chinese reading comprehension. Moreover, Zhu et al. (2009) created two semantic violation conditions (i.e., small and large) by replacing a target word (e.g., "pump") in a normal sentence with either a semantically related word (e.g., "iron") or a semantically unrelated word (e.g., "salt"). They discovered that, when compared with the large violation, the small violation produced greater activation in the ventral regions of bilateral IFG (BA 45), indicating that these regions are related to the integration of the meanings of individual words at a sentence level in Chinese reading comprehension.

However, there are two points in the fMRI studies on reading Chinese mentioned above (i.e., Wang et al., 2008; Zhu et al., 2009) that deserve attention. First, the main findings in those studies are not consistent with each other. Specifically, while the ventral regions of bilateral IFG were found to contribute significantly to semantic processing in Chinese in Zhu et al., such a result was absent in Wang et al. This is puzzling because the ventral regions of the left IFG have been shown to be associated with semantic processing at the word level in a number of Chinese studies (e.g., Chou, Booth, Bitan, et al., 2006; Chou, Chen, Fan, Chen, & Booth, 2009; Chou, Chen, Wu, & Booth, 2009; Deng, Booth, Chou, Ding, & Peng, 2008; Fan, Lee, & Chou, 2010; Liu et al., 2006; Zhang et al., 2004). Second, both Wang et al. and Zhu et al. manipulated lexical information carried by individual words to create semantic and/or syntactic violations within a sentence in Chinese. It is important to note that, unlike in English and many other European languages with alphabetic scripts in which morphosyntactic information is orthographically marked and is therefore salient, morphosyntactic markings are generally lacking in Chinese, which is a noninflective language. Hence, readers of Chinese need to rely on other means (e.g., memory retrieval, context, and word order) to activate the morphosyntactic information and to conduct syntactic processing in reading (Chen, 1992, 1999). Indeed, there is evidence to show that syntactic-category processing is not obligatory in recognizing Chinese words (Wong & Chen, 2011). In addition, because sentence structure is rather flexible in Chinese, word order may not be a very critical/reliable cue for syntactic processing, except in special cases such as in a classifier phrase or in a marked subject–object–verb or object–subject–verb sentence (Chen, 1992, 1999). Thus, simply manipulating the word-level information may not be the most effective way to introduce different types of violations in reading Chinese using the violation paradigm. This is probably why inconsistent findings were found in the mentioned fMRI studies on reading Chinese.

In an attempt to enhance the validity of experimental manipulations in using the violation paradigm to examine the semantic and syntactic processes involved in reading Chinese, the present study introduced the related violations in a relatively more constrained phrase structure in the language (i.e., the classifier phrase, which includes a numeral/demonstrative, a classifier, and a noun). An obligatory classifier system is used in modern Chinese to classify nouns and to build a relation between classifiers and their corresponding nouns (Allan, 1977). In fact, a numeral cannot quantify a noun by itself in the language. Instead, classifiers are needed to be used together with numerals or demonstratives (e.g., "this" and "that") to specify the quantity of an object or to identify particular objects (Myers, 2000). Thus, if a word other than a classifier appears in between a numeral and a noun in a phrase, the phrase would be considered as problematic both syntactically and semantically, whereas if an improper classifier is used, the phrase would be considered as semantically incongruent. In other words, the relations between classifiers and related nouns are constrained by both semantic and structural properties.

Chinese classifiers have been used to address whether semantic processes at different levels of syntactic hierarchy have differential neural manifestations (Zhou et al., 2010). In a commonly used SVO (subject–verb–object) structure of "subject noun + verb + numeral + classifier + object noun", Zhou et al. created a violation between a classifier and its corresponding noun at a lower-phrase level, and a violation between a verb and its corresponding noun at a higher-phrase level. They observed differential N400 effects to reflect the interaction of semantic processes at different levels (lower vs. higher phrase level) to integrate the incoming word into the sentential context. However, given that Chinese classifiers are organized by their semantic features such as shape, size, rigidity, or animacy (Gao & Malt, 2009; He, 2000), little is known about how different types of classifiers are semantically processed at the phrase level and their neural correlates. Consequently, the present study focuses on the semantic processing of two categories of Chinese classifiers, namely count and mass classifiers. Count classifiers are typically used with individual entities, whereas mass classifiers are used with mass-like entities (Huang & Chen, 2009). Behavioral evidence suggests that the count/mass distinction in Chinese classifiers is essentially semantic (Zhang, 2007; Lucy, 1992). The relationship between count classifiers and the related nouns (e.g., a/tiao/river, in which/tiao/means "long and flexible") is generally analogical and relatively fixed (Huang & Chen, 2009), whereas that between mass classifiers and the related nouns may be relatively more diffused and flexible, because mass classifiers can represent standard measures (e.g., a pound of meat), container measures (e.g., a cup of tea), or partitive measures (e.g., a piece of cake) (Myers, 2000; Tai, 1992; Tai & Wang, 1990). Note that processing more diffused semantic features requires (1) selecting the relevant features and (2) ignoring the irrelevant features (Cree et al., 2006). This semantic processing on diffused features has been shown to be associated with brain activity in the ventral regions of the IFG in Chinese (Lee, Booth, Chen, & Chou, 2011).

Following the previous fMRI studies on reading Chinese (i.e., Wang et al., 2008; Zhu et al., 2009), the present study adopted the same violation paradigm to create two violation conditions: the inside-classifier (IC) and the outside-classifier (OC) violations. The IC violation condition was created by changing the correct classifier in the congruent (CON) condition to an inappropriate one either within each sub-type of classifiers or between two sub-types. For instance, an intra-count classifier violation was constructed by replacing the count classifier in the CON condition with an inappropriate count classifier, whereas an inter-classifier violation was created by changing the count classifier in the CON condition to an inappropriate mass classifier, or by changing the mass classifier in the CON condition to an inappropriate count classifier (see Fig. 1 for examples). In addition, the OC violation condition was created by changing the correct classifier in the CON condition to another word commonly used in a different category (i.e., a verb, a noun, or an adjective; as illustrated in Fig. 1).

The present study probed how Chinese classifiers are processed in reading comprehension through both within- and between-class manipulations in the IC and OC conditions, respectively. In the IC conditions, we focused on two sorts of comparisons: the IC violated sentences vs. their corresponding controls and the contrasts between different sub-types of IC violations. If the ventral region of the left IFG plays an active role in Chinese semantic processing (e.g., Zhu et al., 2009), we hypothesized that it would be activated more strongly in the IC violation condition than in the CON condition, because the IC violations are, by definition, semantically, but

	Correct classifier phrases (The classifier is underlined)	Violations of classifier phrases (The violation is underlined)
Inside-classifier violation: Intra-Count	一 面 牆 yi mian qiang a flat wall	一 條 牆 yi tiao qiang a long and flexible wall
Inside-classifier violation: Intra-Mass	一 杯 茶 yi bei cha a cup of tea	一 雙 茶 yi shuang cha a pair of tea
Inside-classifier violation: Inter-classifier	一 張 紙 yi zhang zhi a flat and thin paper	一 場 紙 yi chang zhi an episode of paper
Outside-classifier violation	一 片 葉 yi pian ye a flat and small leaf	一 做 葉 yi zuo ye a make leaf

Fig. 1. Examples of classifier phrase structures for the inside-classifier violation condition (intra-count, intra-mass, and inter-classifier violations) and for the outside-classifier violation condition.

not syntactically, relevant. In addition, it has been proposed that the count-mass distinction in Chinese classifiers is syntactically relevant, but semantically irrelevant (e.g., Chien, Lust, & Chiang, 2003; but see Lucy, 1992; Zhang, 2007, for a different view). If this is indeed the case, then contrasting various sub-types of IC violations would not be expected to produce different patterns of brain activations, because IC violations are semantic in nature. However, if this particular way to differentiate Chinese classifiers is semantically based, then the different IC violations would be expected to produce different results.

Furthermore, if OC violations introduced in a relatively constrained phrase structure are indeed effective in detecting an obstruction in both semantic and syntactic processing, we predicted that such violations would produce greater activation in those brain areas (e.g., BAs 45 and 44) that have been associated with structural and semantic processing during Chinese reading (e.g., Wang et al., 2008; Zhu et al., 2009). Also, to explore the possible impact of introducing lexical violations in reading Chinese through changing word category (i.e., a verb, a noun, or an adjective), we tested whether different OC conditions would produce differential patterns of brain activation after each of them was compared with their relative controls. If syntactic-category processing in lexical access is obligatory and universal (for relevant discussions, see, e.g., Wong & Chen, 2011), then different sub-types of OC violations would be expected to reveal distinct results. Alternatively, given that a context-dependent strategy is commonly adopted in reading Chinese, sentential context, rather than syntactic-category information of individual words, probably plays a more prominent role in syntactic processing (Chen, 1992, 1999; Wong & Chen, 2011). If so, in a Chinese classifier phrase where the structural constraint is relatively clear and strong, the critical factor should be whether the expectation to find a classifier at a classifier position can be fulfilled, but not the syntactic category information of a non-classifier appearing at a classifier position. Following this reasoning, the OC violation and the CON contrast would be expected to produce different results, but various sub-types of OC violations would not be expected to produce distinct results.

2. Materials and methods

2.1. Participants

Thirty-four native speakers of Chinese (mean age = 21.8, SD = 4.0, 15 females) in Taiwan participated in the fMRI study. They were given an informal interview to insure that they met the following inclusionary criteria: (1) right-handedness, (2) normal hearing and normal or corrected-to-normal vision, (3) no history of any language deficits and learning disability. After the administration of the informal interview, informed consent was obtained. The informed consent procedures were approved by the Institutional Review Board at the National Taiwan University Hospital.

2.2. Stimulus characteristics

There were three conditions of trials, the congruent condition, the inside-classifier violation condition, and the outside-classifier violation condition, abbreviated as the CON, the IC, and the OC conditions, respectively. Sixty grammatically correct Chinese sentences with 60 different correct classifiers were used in the CON condition, with 30 count and 30 mass classifiers. Each of these sentences was modified to produce the IC and the OC conditions. The same 60 correct classifiers for the CON condition were re-arranged for the IC condition in the way that a classifier-noun combination formed a meaningless phrase in Chinese. The re-arrangements for the IC condition produced 20 violations of intra-count classifiers, 20 violations of intra-mass classifiers, and 20 violations of inter-classifiers, according to Huang and Chen (2009). The target characters (i.e., the classifiers) were carefully matched for frequency and visual complexity across the three types of IC violations.[1]

For the OC condition, there were 60 different non-classifier words to replace the 60 correct classifiers in the CON condition. These 60 non-classifier words were chosen from three major word categories: 21 nouns, 21 verbs and 18 adjectives, based on their most frequent usage in Academia Sinica balanced corpus (Sinica Corpus, 1998). In the OC condition, the target characters were also matched for frequency and visual complexity across three word categories.[2]

Altogether, each participant received all the 60 sentences, 20 sentences in the CON version, 20 in the IC version, and 20 in the OC version, following proper across-participants counterbalancing. The target characters were matched for frequency and visual complexity across three conditions.[3]

Given that there was a semantic violation in both the IC and the OC conditions, we conducted a rating study to examine whether such a violation was comparable across the two conditions. A separate group of 18 participants were recruited from the same participant pool to rate the semantic plausibility of all sentences on a 5-point scale (ranging from 1 = "extremely unacceptable" to 5 = "fully acceptable"). The average scores were 4.7 (SD = 0.4), 2.7 (SD = 0.5), and 2.5 (SD = 0.4) for the CON, IC, and OC sentences, respectively.[4] The three conditions significantly differed in terms of semantic plausibility, $F(2, 177) = 410.5$, $p < .001$. Pair-wise t-tests indicated that while the two violation conditions were significantly lower than the CON condition ($p < .01$), they had similar semantic plausibility scores ($p > .05$), suggesting that the extent of semantic violation was matched across the two conditions.

In the IC condition, the rating scores of semantic plausibility were further spilt into three violation types. The average scores were 2.7 (SD = 0.6), 2.7 (SD = 0.6), and 2.6 (SD = 0.5) for the intra-count classifier, intra-mass classifier, and inter-classifier violations, respectively, with no significant differences across three types ($p > .05$). In the OC condition, the rating scores of semantic plausibility were further spilt into three categories. The average scores were 2.6 (SD = 0.4), 2.5 (SD = 0.3), and

[1] Average occurrences per 14 million (Sinica Corpus, 1998) for the intra-count classifier, intra-mass classifier, and inter-classifier violations were 4825 ± 7043, 3708 ± 5851, and 7700 ± 11112 (mean ± SD), respectively, with no significant differences across the three types of violations ($F(2, 57) = 1.23$, $p = .30$). The visual complexity of the target characters was matched in terms of the average stoke numbers, which were 11.40 ± 2.72, 11.90 ± 4.58, and 9.50 ± 4.03 (mean ± SD) for the intra-count classifier, intra-mass classifier, and inter-classifier violations, respectively, with no significant differences across the three types of violations ($F(2, 57) = 2.16$, $p = .13$).

[2] Average occurrences per 14 million (Sinica Corpus, 1998) for the nouns, verbs, and adjectives were 11832 ± 17837, 3852 ± 4327, and 8389 ± 9871 (mean ± SD), respectively, with no significant differences across three word categories ($F(2, 57) = 2.28$, $p = .11$). The visual complexity of the target characters was matched in terms of the average stoke numbers, which were 10.09 ± 3.60, 11.29 ± 3.44, and 11.78 ± 4.31 (mean ± SD) for the nouns, verbs, and adjectives, respectively, with no significant differences across three word categories ($F(2, 57) = 1.05$, $p = .36$).

[3] Average occurrences per 14 million (Sinica Corpus, 1998) for the CON, IC, and OC conditions were 5411 ± 8345, 5411 ± 8345, and 8007 ± 12396 (mean ± SD), respectively, with no significant differences across three conditions ($F(2, 177) = 1.38$, $p = .25$). The visual complexity of the target characters was matched in terms of the average stoke numbers, which were 10.93 ± 3.93, 10.93 ± 3.93, and 11.02 ± 3.77 (mean ± SD) for the CON, IC, and OC conditions, respectively, with no significant differences across three conditions ($F(2, 177) = 0.01$, $p = .99$).

[4] Note that, using the same five-point semantic plausibility rating, the difference between the average rating for the CON sentences and that for the violated sentences was about 1.6 in Wang et al. (2008), whereas that in the present study was about 2.1. Moreover, because all subtypes of the violation conditions were firstly compared with the CON condition, the CON condition served as a crucial control in the violation paradigm. In the present study, the semantic plausibility of the CON condition was 4.7, whereas it was 3.9 in the study of Wang et al. (2008). Thus, the study of Wang et al. provided a solid basis, and the present study made a further improvement by introducing a constrained classifier phrase to enhance the validity of related manipulations.

2.7 (SD = 0.5) for the nouns, verbs, and adjectives, respectively, with no significant differences across three categories ($p > .05$).

2.3. Functional activation task

Trials lasted 5930 ms and consisted of a fixation cross (1000 ms), followed by a sentence (4930 ms). The display duration of a sentence was slightly shorter than 5 s that was considered a cut-off point for outliers (Wang et al., 2008). All characters from the sentence were presented at once centered on the screen. The participants were instructed to make a semantic congruency judgment by pressing a left or a right button during the presentation of the sentence. There were 30 baseline events randomly mixed with sentences to better deconvolve the responses to the CON, IC, and OC conditions (Burock, Buckner, Woldorff, Rosen, & Dale, 1998; Chou, Chen, Fan, et al., 2009; Chou, Chen, Wu, et al., 2009). The baseline events were adopted from Shaywitz et al. (1998), using two kinds of symbols visually similar to experimental stimuli with a similar length (i.e., 14 symbols in a row just like the average length of all sentences, which was 14 characters). The participants were instructed to make a Yes response to symbol 1 and a No response to symbol 2.

2.4. MRI data acquisition

Participants lay in the scanner with their head position secured. An optical response box was placed in the participants' right hand. The head coil was positioned over the participants' head. Participants viewed visual stimuli projected onto a screen via a mirror attached to the inside of the head coil. This study adopted an event-related design. Each participant performed two functional runs. Each of the two runs took 4 min and 35 s. Each functional run had 138 image volumes.

All images were acquired using a 3 T Siemens scanner. Gradient-echo localizer images were acquired to determine the placement of the functional slices. For the functional imaging studies, a susceptibility weighted single-shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was used. Functional images were interleaved from bottom to top. The following scan parameters were used: TE = 24 ms, flip angle = 90°, matrix size = 64 × 64, field of view = 25.6 cm, slice thickness = 3 mm, number of slices = 34; TR = 2000 ms. In addition, a high resolution, T1 weighted 3D image was acquired (TR = 1560 ms, TE = 3.68 ms, flip angle = 15°, matrix size = 256 × 256, field of view = 25.6 cm, slice thickness = 1 mm, number of slices = 192). The orientation of the 3D image was identical to the functional slices. The task was administered in a pseudorandom order for all participants, in which the order of the CON, IC (count and mass), OC (noun, verb, and adjective), and baseline trials was optimized for event-related design (Burock et al., 1998). We used the Optseq script for randomized event-related design (http://surfer.nmr.mgh.harvard.edu/optseq, written by D. Greve, Charlestown, MA) that implemented Burock et al. (1998)'s approach.

2.5. Image analysis

Data analysis was performed using SPM5 (Statistical Parametric Mapping). The functional images were corrected for differences in slice-acquisition time to the middle volume and were realigned to the first volume in the scanning session using affine transformations. No participant had more than 3 mm of movement in any plane. Co-registered images were normalized to the MNI (Montreal Neurological Institute) average template (12 linear affine parameters for brain size and position, 8 non-linear iterations and 2 × 2 × 2 nonlinear basis functions). Statistical analyses were calculated on the smoothed data (10 mm isotropic Gaussian kernel), with a high pass filter (128 s cutoff period).

The data from each participant were entered into a regression model using an event-related analysis procedure with correct trials (Penny & Holmes, 2003). Sentences were treated as individual events for analysis and modeled using a canonical HRF (Hemodynamic Response Function) with temporal derivatives. There were four major event types: the CON, IC, OC, and baseline conditions. Random-effects analysis using one-sample t-tests across all participants was used to determine whether activation during a contrast was significant (i.e., parameter estimates were reliably greater than 0). First, we compared the IC with the CON conditions, and the OC with the CON conditions in the whole brain analysis. Second, we conducted bi-directional comparisons between the three sub-types of violations in the IC condition, after each of them was compared with their corresponding controls, with anatomical masks of bilateral inferior frontal gyri due to our a priori hypothesis. Third, we conducted 6 pairwise comparisons among verbs, nouns, and adjectives in the OC violation, after each of them was compared with their corresponding controls, with a mask of a combined brain map from the CON, IC, and OC conditions with a logical "OR" operation ($p < .05$ uncorrected). For all analyses, the threshold was set to $p < .05$ FDR (false discovery rate) corrected at the voxel level with a cluster size greater than 10 voxels.

3. Results

3.1. Behavioral performance

The accuracy rates (mean ± SD) for the CON, IC, and OC conditions were 96 ± 4%, 91 ± 8%, and 94 ± 7%, respectively. A one-way ANOVA on accuracy was significant, $F(2, 66) = 6.29$, $p < .05$. The post hoc tests revealed that the IC condition was less accurate than the CON condition, a paired $t(33) = 3.34$, $p < .05$. However, no reliable difference was found between the CON and OC conditions, a paired $t(33) = 1.97$, $p > .05$; nor between the IC and OC conditions, a paired $t(33) = 1.72$, $p > .05$. The reaction times (mean ± SD) for the CON, IC, and OC conditions were 2272 ± 527 ms, 2068 ± 467 ms, and 2006 ± 437 ms, respectively.[5] A one-way ANOVA on reaction times was significant, $F(2, 66) = 18.39$, $p < .05$. The post hoc tests revealed that the CON condition was significantly slower than the IC and the OC conditions, both paired t's(33) = 3.78 and 5.09, both p's < .05. Moreover, the IC condition was significantly slower than the OC condition, a paired $t(30) = 2.39$, $p < .05$.

In the IC condition, the accuracy rates for the intra-count, intra-mass, and inter-classifier violations were 91 ± 12%, 92 ± 11%, and 90 ± 13%, respectively, with no significant differences across the three types of violations, $F(2, 66) = 0.30$, $p > .05$. The reaction times for the intra-count, intra-mass, and inter-classifier violations were 2064 ± 552 ms, 2015 ± 489 ms, and 2133 ± 451 ms, respectively, with no significant differences across the three types of violations, $F(2, 66) = 2.49$, $p > .05$.

In the OC condition, the accuracy rates for the nouns, verbs, and adjectives were 95 ± 10%, 97 ± 10% and 92 ± 12%, respectively. A one-way ANOVA on accuracy was not significant, $F(2, 66) = 2.04$, $p > .05$. The reaction times (mean ± SD) for the nouns, verbs, and adjectives were 1915 ± 422 ms, 2058 ± 486 ms, and 1999 ± 483 ms, respectively. A one-way ANOVA on reaction times was significant, $F(2, 66) = 4.11$, $p < .05$. The post hoc tests revealed that the verb condition was significantly slower than the noun condition, a paired $t(33) = 3.29$, $p < .05$. However, no reliable difference was found between the noun and adjective conditions, a paired $t(33) = 1.66$, $p > .05$; nor between the verb and adjective conditions, a paired $t(33) = 1.07$, $p > .05$.

3.2. Brain activation patterns

All activation differences are reported in tables. Table 1 shows greater activation in the left inferior frontal gyrus (BA 45) for the contrast of the IC vs. the CON condition, and greater activation in the left inferior frontal gyri (BA 45, 44) for the contrast of the OC vs. the CON condition.

Table 2 shows the results of the pairwise comparisons of the three subtypes of IC conditions (i.e., intra-count, intra-mass, and inter-classifier violations), after comparing each of them with their respective control. The contrast of intra-mass vs. intra-count classifier violations produced greater activation in the ventral regions

[5] Given that each individual sentence was entirely presented on a computer screen in the present study, one might ask weather or not our participants had performed the semantic congruency judgment without reading through the whole sentence. This does not seem very likely for the following reasons. First, if our participants only checked the semantic congruence between the relevant words rather than reading the whole sentence, then one would expect to find the overall reaction time being relatively short (e.g., less than one second; Chen et al., 1995). Yet, the average reaction time in the present study was about two seconds, which is comparable to those reported in other studies using a similar task and similar sentence stimuli (e.g., Wang et al., 2008; Zhu et al., 2009). Second, when stimuli were presented in a rapid serial visual presentation (RSVP) using the same violation paradigm, and when participants were instructed to make their responses after the full sentence had been presented, the pattern of results was basically the same as that in using a simultaneous presentation for displaying the entire sentence (Zhou, Ye, Cheung, & Chen, 2009). Moreover, we asked 10 additional participants who did not participate in the present study to perform the semantic congruency judgment on the same stimuli as those used in the present study and subsequently to recognize words appeared at a random position in each sentence (to prevent they from reading a certain part of each sentence). With similar recognition accuracy rates across different conditions, the pattern of response times is the same as that reported in this study.

Table 1
Brain activations for the inside-classifier (IC) violation and the outside-classifier (OC) violation conditions separately compared with the congruent (CON) condition.

Condition	Regions	H	BA	*z*-Test	Voxels	*x*	*y*	*z*
IC–CON	Inferior frontal gyrus	L	45	4.26	521	−54	15	15
OC–CON	Inferior frontal gyrus	L	45	4.60	576	−54	18	9
	Inferior frontal gyrus	L	44			−54	9	15

Note. H: hemisphere; L: left; R: right; BA: Brodmann's Area. Coordinates of activation peak(s) within a region based on a *z*-test are given in the MNI stereotactic space (*x*, *y*, *z*). Voxels: number of voxels in cluster at $p < .05$ FDR (false discovery rate) corrected, only clusters greater than 10 are presented.

Table 2
Brain activations for the pairwise comparisons of the three subtypes (i.e., intra-count, intra-mass, and inter-classifier violations) in the inside-classifier violation condition, after each of them was compared with their corresponding control.

Condition	Regions	H	BA	*z*-Test	Voxels	*x*	*y*	*z*
Intra-mass vs. intra-count classifier	Inferior Frontal Gyrus	R	45	3.91	37	60	18	15
	Inferior Frontal Gyrus	R	47	3.51	21	39	18	−3
Inter-classifier vs. intra-count classifier	Inferior Frontal Gyrus	R	47	3.08	42	39	24	−9
Inter-classifier vs. intra-mass classifier	–							

Note. See Table 1 note. The analyses were done with anatomical masks of bilateral inferior frontal gyri.

of the right inferior frontal gyrus (BA 47, 45) (Fig. 2). Similarly, the contrast of inter-classifier vs. intra-count violations produced greater activation in the right inferior frontal gyrus (BA 47). However, no significant area of activation was found for the contrast of inter-classifier vs. intra-mass violations.

The six pairwise comparisons among the three sub-types of OC violation conditions (i.e., verbs, nouns, and adjectives) did not reach significance, after comparing each of them with their corresponding control.

4. Discussion

A special property of the Chinese language is that classifiers are needed to be used with numerals to quantify nouns. The aim of this fMRI study was to identify brain activation related to the semantic and syntactic processing of Chinese classifier phrases during reading for comprehension. In other words, our focus is on the Chinese language, but not on cross-linguistic comparisons. Given that a similar need of using classifiers to quantify nouns

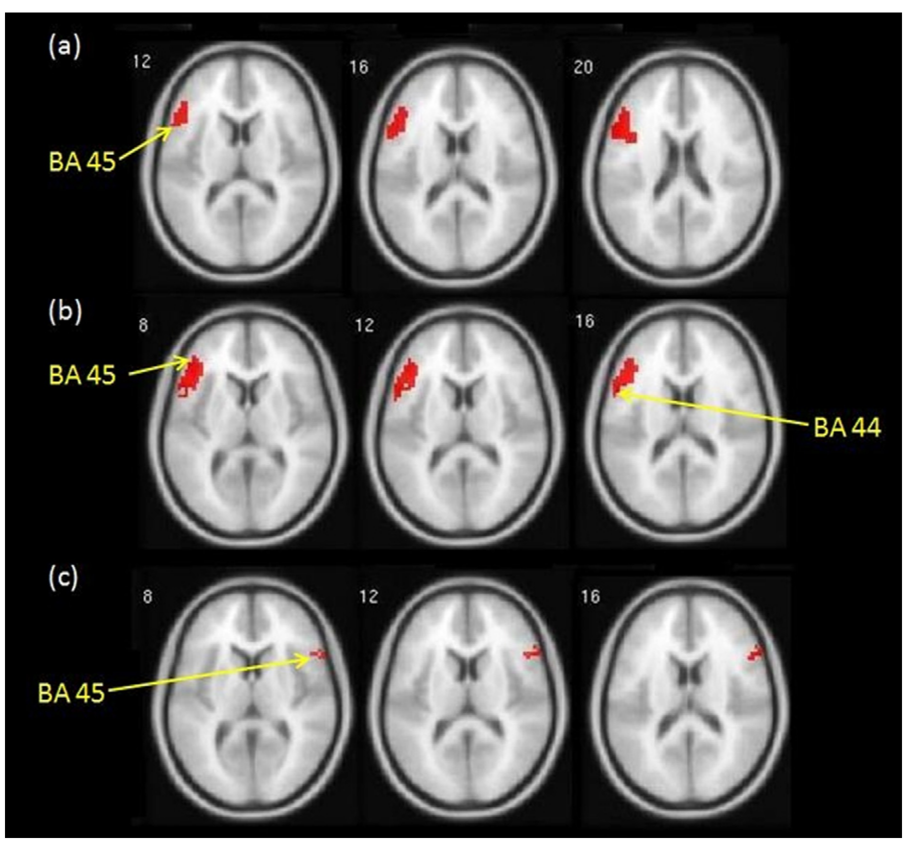

Fig. 2. Brain activations. (a) The contrast of the inside-classifier (IC) violation vs. the congruent (CON) condition produced greater activation in the left frontal gyrus (BA 45). (b) The contrast of the outside-classifier (OC) violation vs. the CON condition produced greater activation in the left frontal gyrus (BA 45, BA 44). (c) The contrast of the intra-mass vs. intra-count classifier violations produced greater activation in the right inferior frontal gyrus (BA 45) for the IC vs. the CON condition.

does not exist in European languages such as English, our findings are not used to distinguish syntactic/semantic processing between Chinese and other languages. In the present study, participants made semantic congruency judgments on three kinds of sentences containing a classifier phrase structure: the congruent (CON), the inside-classifier (IC) violated, and the outside-classifier (OC) violated. We found three major results. First, the contrast of the IC vs. CON condition showed greater activation in the ventral region of the left IFG (BA 45). Second, comparing different types of IC violations revealed that the ventral regions of the right IFG (BAs 45 and 47) are also related to the processing of Chinese classifiers. Finally, the contrast of the OC vs. CON condition produced greater activation in the posterior dorsal and ventral regions of the left IFG (BAs 44 and 45). These results are discussed in turn in the following paragraphs.

First, the present study showed that, relative to the CON condition, the IC violation (i.e., replacing a correct classifier with an inappropriate one) produced greater activation in the ventral region of the left IFG (BA 45). A similar activation pattern was also found when contrasting the OC violation and CON conditions. According to the design logic of the present and previous studies using the violation paradigm (e.g., Wang et al., 2008), both IC and OC conditions involved a similar violation in semantic processing. In addition, the stimuli in the two conditions were well-matched in their extent of semantic violation, as reflected by the semantic plausibility rating results. Furthermore, using the same violation paradigm in Chinese, relatively small semantic violations produced greater activation in this region, as compared with relatively large semantic violations (Zhu et al., 2009). Apart from these, the ventral region of the left IFG has been identified to be involved in various semantic tasks in English and other European languages during sentence processing such as ambiguity resolution (Rodd et al., 2005), meaning judgment (Dapretto & Bookheimer, 1999), thematic analysis (Newman, Just, Keller, Roth, & Carpenter, 2003), comprehending metaphoric sentences (Stringaris et al., 2007), or meaning acquisition from context (Mestres-Missé et al., 2008). Therefore, the greater activation in the left BA45 is likely to reflect an additional demand on introducing a semantic obstruction in the classifier phrases in the present study.

Note that because the stimuli in the control and the various violation conditions may differ in more than one aspect (e.g., difficulty in semantic integration, need to detect and fix a violation, and type of a required correct response), one might ask whether the activation we observed in the mid-ventral region of the left IFG could be attributed to factors other than semantic processing. Although these other factors were not directly manipulated in the present study, we do not think they can be used to form the most appropriate account for the present finding. This is because, using the same violation paradigm, Zhu et al. (2009) carefully removed the potential confound of non-semantic factors by comparing sentences with different degrees of semantic violation and found that the same region of bilateral IFG (BA 45) was involved in semantic processing during Chinese reading for comprehension, which is compatible with the present finding. Thus, the activation in the left BA45 is more likely to reflect semantic processing than processing of other non-semantic factors in reading Chinese.

Interestingly, while the present study and Zhu et al. (2009) found a consistent pattern of brain activation related to semantic processing in reading Chinese, a similar pattern was absent in Wang et al. (2008). Since the main difference between Wang et al. and the present study lies in the type of stimuli used, introducing lexical violations in relatively more constrained phrase structures is likely to be responsible for our success in revealing greater activation in this particular brain region for semantic processing in reading Chinese.

Moreover, we compared different sub-types (mass vs. count) of IC violations to examine how different types of semantic features were processed. Such contrasts (i.e., inter-classifier vs. intra-count and intra-mass vs. intra-count) produced greater activation in the ventral regions of the right IFG (BAs 47 and 45), although a similar pattern was absent in the contrast of inter-classifier vs. intra-mass conditions. This finding suggests that processing mass- and count-classifiers may involve different brain activations, because a distinctive component of mass classifiers can be singled out from the contrasts of inter-classifier (i.e., a count to mass classifier change or vice versa) vs. intra-count and intra-mass vs. intra-count, but not from that of inter-classifier vs. intra-mass. Note that the relationship between mass classifiers and the corresponding nouns is considered to be more diffused and flexible, but that between count classifiers and the related nouns is both analogical and relatively fixed. In addition, the ventral regions of the left IFG have been shown to play a critical role in semantic tasks during sentence processing (Dapretto & Bookheimer, 1999; Mestres-Missé et al., 2008; Newman et al., 2003; Rodd et al., 2005; Stringaris et al., 2007), whereas the corresponding regions in the right IFG have been associated with extensive search and selection for discriminative features (Chou, Booth, Burman, et al., 2006) or relatively more diffused semantic processing (Beeman, 2005; Zhu et al., 2009). Hence, the present finding of greater activation in the ventral regions of the right IFG may reflect a more extensive search for diffused semantic information in processing an IC violation involving mass classifiers, suggesting that the right-hemisphere homologue of the left IFG might have been recruited to perform semantic processing and that the mass-count distinction in Chinese classifiers is semantically relevant (e.g., Lucy, 1992; Zhang, 2007).[6]

However, in addition to semantic processing, the right IFG has also been associated with response inhibition (e.g., Aron, Robbins, & Roldrack, 2004) and attentional control (e.g., Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010). Thus, one might ask whether the right IFG activation observed in the present study should be attributed solely to semantic processing. Note that if the observed right IFG activation reflects inhibition of prepotent responses or attentional control, the same pattern of activation should also be found in the contrasts of OC violation vs. CON and inter-classifier vs. intra-mass, or within the pairwise contrasts among the three sub-types of OC violations, but such results were not found. In fact, the right IFG activation was only observed within the pairwise contrasts among the sub-types of IC violations. Hence, non-semantic factors do not seem to be able to account for the overall pattern of our findings. Altogether, when contrasting the IC vs. CON, in which both positive and negative responses were involved, and the different sub-types of IC violations, in which only

[6] Our rationale to propose a role of semantic process in the count-mass distinction in Chinese classifiers is also based on the following reasons. First, the semantic explanation for the count-mass distinction in classifiers is derived from the contrast of the IC violation vs. the congruent condition and such a contrast is presumably to reflect semantic processing. Second, both count and mass classifiers can be placed along a semantic continuum (Lucy, 1992; Zhang, 2007). Hence, such a distinction may be semantically relevant, at least in the context of Chinese. Note that although the strictly semantic relevance explanation can readily account for our results, it does not necessarily preclude the involvement of syntactic processing. Actually, if we assume that both semantic and syntactic processing occur in a parallel manner, but the former is stronger than the latter, then the present findings can also be account for by such an explanation. However, although the present findings cannot be used to differentiate between the strictly semantic relevance explanation and the semantic dominance explanation, they do suggest that the role of semantic processing is more critical, relative to that of syntactic, in the mass-count distinction in Chinese classifiers. Finally, the above discussion is restricted to classifiers in Chinese only. It has been argued that, at least in English, the count/mass distinction is language-specific and somewhat arbitrary and thus may be hard to say categorically that such a distinction is syntactic or semantic (Vigliocco, Vinson, Martin, & Garrett, 1999; but see Iwasaki, Vinson, & Vigliocco, 2010).

negative responses were involved, the activation pattern in the ventral regions of both right and left IFG provides clear evidence to suggest that these particular regions play a semantic role in dealing with the IC violations.

Third, with the use of relatively more constrained classifier phrases, the contrast of OC violation vs. CON produced greater activation in the mid-ventral region (BA 45) and the posterior dorsal region (BA 44) of the left IFG. This is consistent with the finding of Wang et al. (2008) that changing word category resulted in both semantic and syntactic violations in sentence comprehension in Chinese, although Wang et al. did not find greater activation in the left BA45. Note that greater activation in the posterior region (BA 44) of the left IFG has been interpreted as reflecting the processing of general structure (e.g., building a local phrase structure) while reading a sentence (Ni et al., 2000; Thompson et al., 2007; Wang et al., 2008). Also, this region has been found to be associated with working memory mechanisms relevant to sentence processing, suggesting that this region is preferentially engaged in working-memory demanding parses (Hoen, Pachot-Clouard, Segebarth, & Dominey, 2006; Uchiyama et al., 2008). Although our finding of left IFG activation probably could be attributed to an increased working-memory demand this is not likely because stimulus characteristics and task difficulty were carefully matched across the OC violation and the CON conditions.

In the OC violation condition, direct comparisons among verbs, nouns, and adjectives showed no regions of significant difference. Interestingly, this finding is in line with that of others in English, demonstrating overlapping activation regions for comparing verbs with nouns (Thompson et al., 2007; Tyler, Russell, Fadili, & Moss, 2001). Note that the relative impact on reading comprehension should be larger in the OC violation condition than in the IC violation condition, because an OC violation greatly interrupted the anticipation of an appropriate context between a numeral/demonstrative and a noun in processing a typical Chinese classifier phrase structure. This is probably why an incongruent judgment could be made faster to a sentence containing an OC violation, relative to that containing an IC violation. The salient OC violation could override the potential effect of word category (i.e., replacing the original classifier with a verb, a noun, or an adjective). Indeed, our null result in comparing different types of OC violations is consistent with the idea that in a highly constrained context, the context rather than the properties of individual words may play a stronger role during reading comprehension (Ferreira, Ferraro, & Bailey, 2002).

5. Conclusion

The present fMRI study examined brain activation of classifiers in Chinese reading for comprehension. We found that the ventral region of the left IFG (BA 45) was activated by both inside-classifier (IC) and outside-classifier (OC) violations that produced an obstruction in semantic processing in a classifier phrase, suggesting that this area is involved in semantic processing of classifier phrases. In addition, the ventral regions of the right IFG (BAs 47 and 45) were particularly activated by IC violations involving mass classifiers, but not by those involving count classifiers, indicating that processing different types of classifiers may involve distinct brain activations and that the mass-count distinction in Chinese classifiers is semantically, rather than, syntactically relevant. Finally, the posterior dorsal region of the left IFG (BA 44) was only activated by OC violations that introduced both semantic and syntactic obstacles in processing classifier phrases, but not by other types of violations, suggesting that this area is involved in processing the syntactic structure of classifier phrases. The present findings thus indicate that different parts of the inferior frontal gyrus contribute to syntactic and semantic processing of classifier phrases in reading Chinese, providing support for the idea that distinct frontal regions are involved in the various processes in comprehension (Friederici & Kotz, 2003). Further work is needed to explore how these distinct regions interact to influence language processing.

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