Running title: HEMISPHERIC INVOLVEMENT IN PROCESSING OF IDIOMS

Hemispheric Involvement in the Processing of Chinese Idioms: An fMRI Study

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Abstract

Although the left hemisphere is believed to handle major language functions, the role of the right hemisphere in language comprehension remains controversial. Recently researchers have investigated hemispheric language processing with figurative language materials (e.g., metaphors, jokes, and idioms). The current study capitalizes on the pervasiveness and distinct features of Chinese idioms to examine the brain mechanism of figurative language processing. Native Chinese speakers performed a non-semantic task while reading opaque idioms, transparent idioms, and non-idiomatic literal phrases. Whole-brain analyses indicated strong activations for all three conditions in an overlapping brain network that includes the bilateral inferior/middle frontal gyrus and the temporo-parietal and occipital-temporal regions. The two idiom conditions elicited additional activations in the right superior parietal lobe and right precuneus. Item-based modulation analyses further demonstrated that activation amplitudes in the right angular gyrus, right superior parietal lobule and right precuneus, as well as left inferior temporo-occipital cortex, are negatively correlated with the semantic transparency of the idioms. These results suggest that both hemispheres are involved in idiom processing but they play different roles. Implications of the findings are discussed in light of theories of figurative language processing and hemispheric functions.

Keywords: fMRI; Chinese; idiom processing; fine-coarse coding theory; hemispheric language functions; semantic transparency

1 Introduction

Figurative language, such as metaphors, idioms, jokes, ironies, and sarcasm are pervasive in our daily speech to enable simple and elegant communications. Although the intended meaning of figurative language usually cannot be directly derived from the literal meaning of the constituent words, as in “love is a journey” or “kick the bucket”, native speakers can comprehend them effortlessly. Much research attention has been devoted to explore how this comprehension happens in our brain. However, the question about the involvement of left hemisphere (LH) versus right hemisphere (RH) during the processing of figurative language remains controversial. The present study addressed this issue by examining the neural mechanisms of figurative language comprehension, with a specific emphasis on the processing of idioms in Chinese.

1.1. RH vs. LH involvement in figurative language processing: Current evidence

The specific role of the RH in the comprehension of figurative language was advocated by a number of early neuropsychological studies that reported that right hemisphere damaged (RHD) patients showed poorer performance on figurative language and relatively good performance on literal sentences. For example, Van Lanker and Kempler (1987) found that in a sentence-to-picture matching task, left hemisphere damaged (LHD) patients performed worse on literal sentences than on idioms (e.g., *keep a stiff upper lip*) and formulaic speech (e.g., *have a nice day*), while RHD patients showed impairment only on idioms and formulaic speech. However, several other studies (Gagnon et al., 2003; Giora et al., 2000; Zaidel et al., 1995, 2002) have failed to support the notion that the RH is selectively involved in processing figurative language. For instance, Gagnon et al. (2003) reported that both RHD and LHD patients were impaired in processing metaphoric word meanings in two different tasks. Moreover, Zaidel et al. (1995) reported a reverse pattern: the LHD patients

showed a selective deficit in processing metaphorical meanings.

Neuroimaging techniques (e.g., fMRI and PET) in the last two decades further contributed to the investigation of the issue of hemispheric involvement in figurative language processing by examining a normal healthy population (see a recent review by Bohrn et al., 2012). Several of these studies have reported positive evidence for the notion that the RH selectively contributes to figurative language processing. A PET study conducted by Bottini et al. (1994) presented participants with literal sentences and novel metaphors that were either literally plausible or literally implausible, and asked them to perform a plausibility judgment task. The authors found that processing of literal sentences and that of metaphors elicited similar activations in the LH (including prefrontal cortex, the middle and inferior temporal gyri, parietal regions, and precuneus (PCu)), but processing of metaphors additionally activated several areas in the RH (including inferior frontal gyrus (IFG), and posterior temporal cortex). Furthermore, in a repetitive transcranial magnetic stimulation (rTMS) study, Pobric, Mashal, Faust, and Lavidor (2008) reported a causal relationship between the interpretation of novel metaphors and activity of the right posterior superior temporal sulcus (pSTS). These authors asked right-handed participants to perform a semantic judgment task on literal, conventional metaphoric, novel metaphoric expressions, and unrelated word pairs, and they observed that rTMS of right pSTS disrupted processing of novel but not conventional metaphors, whereas rTMS over the left IFG selectively impaired processing of literal word pairs and conventional but not novel metaphors. Hence, this study suggested that the RH may be critically involved in at least novel metaphor processing, and also importantly, that the characteristics (novelty in this case) of figurative language are critical for understanding the issue of hemispheric specificity. These possibilities were further confirmed by several other studies that

consistently observed more RH involvement on novel metaphoric meaning only (Mashal et al., 2005, 2007; Schmidt et al., 2007; see also review Bohrn et al., 2012 and Yang, 2014).

In contrast to these findings, other studies have reported no more involvement of RH or even LH predominance during figurative language processing (Kacinik and Chiarello, 2007; Lee and Dappretto, 2006; Oliveri et al., 2004; Rapp et al., 2004, 2007; Stringaris et al., 2007; see also reviews in Bohrn et al., 2012; Rapp et al., 2012; Yang, 2014). For example, Rapp et al. (2004) also examined the neural correlates of metaphor processing at the sentence level. Their stimuli were metaphorical and literal sentences pairs that were closely matched for syntactic structure, word frequency, connotation and tense. Comparison of metaphorical with literal meanings yielded no evidence of RH involvement in metaphor processing, as the increased activation was exclusively observed in LH. In another fMRI study (Stringaris et al., 2007) participants read metaphoric, literal, or nonsense sentences and decided whether the sentences made sense or not. Metaphoric sentences elicited greater activation than did literal sentences in the LH including IFG, precentral gyrus, and inferior parietal lobe, as well as in the right middle temporal gyrus (MTG).

A few other studies have observed a bilateral network for figurative language processing when compared with literal language processing (Lauro et al., 2008; Rizzo et al., 2007; Zimplyeni et al. 2007). Rizzo, Sandrini and Papagno (2007) conducted an rTMS study and found that stimulations to the dorsolateral prefrontal cortex in both LH and RH led to impaired performance on idioms in a sentence-to-picture matching task. An fMRI study by Zemplyeni, Haverkort, Renken and Stowe (2007) showed that the bilateral IFG and the left MTG were more activated in the processing of idioms compared with that of literal sentences, but the right MTG was only involved in the

processing of ambiguous idioms, phrases that can have both a literal interpretation and a idiomatic interpretation in different sentence contexts (e.g., ‘*kick the bucket*’ or ‘*smell a rat*’). The authors suggested that the additional activations in the RH could be attributed to increased demands on ambiguity processing. Lauro, Tettamanti, Cappa and Papagno (2008) also found that idiom comprehension elicited greater bilateral activation than literal sentences. Using an effective connectivity analysis these authors showed that a bilateral prefrontal network played a crucial role in the selection between alternative sentence meanings. The authors hypothesized that the RH is involved in maintaining multiple interpretations and that sustained activation of inconsistent meanings might be useful in case a reinterpretation is needed (Lauro et al.; see also Kacinik and Chiarello, 2007).

1.2. The fine-coarse semantic coding theory

Although the findings regarding the role of the RH in figurative language processing are inconsistent, a specific role of the RH in higher-level language processing fits well with patient data, which led to the theoretical proposal of “fine-coarse semantic coding”, as articulated by Beeman (1998), Beeman & Chiarello (1998), and Jung-Beeman (2005). According to this hypothesis, the LH is responsible for processing fine linguistic information, such as closely related and dominant word meanings or semantic features, while the RH is involved in processing coarse semantic information, such as establishing relations between weak and disperse semantics, organizing pragmatic information, and reinterpreting language stimuli. This characteristic of RH plays significant roles when understanding natural language, particularly figurative language or unusual constructions. Supporting evidence included patient data as discussed in section 1.1., data from healthy subjects with visual hemi-field studies (Beeman et al., 1994), and other fMRI studies (St. George et

al., 1999), and sentence or text reading studies in which inference drawing, syntactic repairing, and narrative event sequencing processes are involved (e.g., Mason and Just, 2004; Meyer et al., 2000; Kircher et al., 2001; Knutson et al., 2004).

Understanding of figurative language like metaphors and idioms requires the activation of distantly related concepts, because their figurative meanings are usually more distant to the dictionary definitions of the words than literal meaning; as such, the processing of figurative meanings might depend heavily on the language user's ability to activate a broader set of semantic associations in order to integrate weakly related words into meaningful linguistic expressions. Specifically, different idioms can vary significantly on semantic transparency, a measure of the distance between figurative meanings and literal meanings. We can roughly categorize idioms into opaque idioms (e.g. *kick the bucket*) versus transparent idioms (e.g. *pop the question*): for the former, the idiomatic meaning is arbitrary and cannot easily be derived from the constituent words, whereas for the latter, the figurative meaning can be at least partly derived from their constituents. However, transparency of idioms has not so far been investigated with regard to hemispheric specialization of figurative language comprehension. According to the fine-coarse coding theory, more involvement of RH would be expected for opaque idioms than for transparent idioms if both their figurative and literal meanings are activated during processing. Related to the effect of semantic transparency are a few previous studies that have investigated the processing of ambiguous idioms and have reported a significant RH advantage only for ambiguous idioms (Zempleni et al., 2007; Mashal et al., 2008). In these studies, the figurative meaning of ambiguous idioms, as compared with that of unambiguous idioms, is semantically more distant to the literal meanings of the constituent words.

1.3. The graded salience hypothesis

With regard to the role of the RH in figurative language processing, some researchers have attributed RH activity to factors such as novelty of the figurative expressions as described above (Mashal et al., 2005; Schmidt et al., 2007). They argued that the RH is not specifically involved in figurative meaning comprehension; instead it is engaged in processing novel stimuli. Giora (1997, 2003, 2007) proposed the graded salience hypothesis and suggested that studies only testing moderately to very familiar expressions (mostly metaphors) would preferentially activate the LH, whereas studies testing unfamiliar language expressions would activate the RH. The graded salience hypothesis advocates, instead of the putative literal vs. non-literal dichotomy, a continuum that is modulated by the familiarity/novelty of expressions, and emphasizes the salience of a particular meaning as a function of its familiarity or frequency. According to this hypothesis, the RH is more likely to be involved in the processing of less salient interpretations and more novel meanings of words, whereas the LH is more likely to be involved in the processing of more familiar and frequent meanings.

To test the graded salience hypothesis, Mashal, Faust, Hendler and Jung-Beeman (2007) conducted an fMRI study to examine brain activations for novel metaphors (e.g., *pearl tears*), familiar metaphors (e.g., *bright student*), literal word pairs (e.g., *water drops*), and unrelated words pairs (e.g., *road shift*). Participants were asked to silently judge whether the two words in each pair were metaphorically related, literally related, or unrelated, and the results showed that compared with familiar metaphors, novel metaphors elicited stronger activations in the right pSTS, the right IFG and the left middle frontal gyrus (MFG). In addition, the right pSTS was also more strongly activated when novel metaphors were compared with literal and unrelated word pairs. These results suggest a special role of the RH, in particular the

right pSTS, in processing novel metaphors and in constructing online associations between two distantly related words. In another study using familiar ambiguous idioms (e.g., *'get off your high horse'*), Mashal, Faust, Hendler and Jung-Beeman (2008) found that compared with processing of figurative meanings of idioms (i.e., *'do not act like you are better than anyone else'*), processing of literal meanings of idioms (i.e., *'get off the horse'*) showed more activations in the right MTG, right superior temporal gyrus (STG), right PCu and the bilateral anterior insula, whereas processing of idiomatic interpretations of idioms and literal interpretations of literal sentences (e.g., *'get off your high ladder'*) involved left brain regions. Since the literal meanings, for familiar ambiguous idioms, are subordinate or non-salient interpretations, and the figurative meanings are dominant or salient, the authors claimed that the RH is involved in processing non-salient meaning, regardless of its figurativeness, whereas the LH is involved in processing salient meaning.

1.4. Significant factors contributing to figurative language processing

Recent studies have shown that several other factors, in addition to semantic transparency and familiarity/novelty discussed above, can influence the RH activation in figurative language processing (for reviews, see Bohrn et al., 2012; Rapp et al., 2012; Yang, 2014). These include factors such as task difficulty and stimulus complexity (e.g., Kasparian, 2013; Schmidt et al., 2009). For example, task difficulty has been assumed to be one reason why it is hard to obtain a consistent picture of the specific brain areas involved in figurative language processing. Bottini et al (1994) observed more activation in RH for metaphor than that for literal sentences, but this pattern was questioned because it involved confounds of task difficulty given that more mistakes were made by participants on metaphors than that on literal sentences (see Lee and Dapretto, 2006; Stringaris et al., 2007). In addition, most of the tasks that

have been used rely strongly on the participants' explicitly judgment on or selection of the meanings, including plausibility judgment (Schmidt et al., 2007), semantic judgment (Faust and Mashal, 2007; Proverbio et al., 2009), truth judgment (Faust and Weisper, 2000) and meaningfulness judgment (Stringaris et al., 2007). The relatively high demand on executive functions such as selection, decision, or inhibition of lexical and semantic aspects of words in these tasks possibly exaggerates the involvement of some brain areas, i.e., the bilateral prefrontal cortex, although these processes or mechanisms contribute significantly, perhaps indispensably to figurative language comprehension.

Another factor affecting figurative language comprehension may be stimulus complexity. As with task difficulty, more complex material will elicit more RH involvement. Most previous studies have used sentential contexts (Bottini et al., 1994; Lauro et al., 2008; Stringaris et al., 2007; Uchiyama et al., 2012; Zempleni et al., 2007), and a few studies have used word pairs (Mashal et al., 2007) or bare idioms (Mashal et al., 2008). A meta-analysis study by Yang (2014) found that the contrast of metaphorical sentences versus literal sentences indicated significant activity in areas of bilateral brain regions that included the right IFG (BA47), whereas the contrast of metaphorical words versus literal words revealed significant effects only in the left MFG (BA9) and no effect was found in the RH. Bohrn, Altmann, and Jacobs (2012) provided an overview of the problems associated with the various types of stimuli and tasks in their review paper.

A third factor that is critical for the study of figurative language comprehension, especially idiom comprehension, is transparency of idioms. Semantic transparency is different from familiarity, in that it depends on how easy it is to derive the figurative meaning from the literal meanings of the constituent words. Usually, as described

above in 1.2, we can categorize idioms into opaque and transparent ones, and there have been psycholinguistic studies that suggest that the processing of these two types of idioms might involve different mechanisms (see Swiney and Cutler, 1979; Tabossi and Zardon, 1995). However, no neuroimaging studies have investigated transparency of idioms with regard to hemispheric specialization of figurative language comprehension. One might hypothesize that in light of the previous theoretical proposals as discussed in sections 1.2 and 1.3, transparency might play an important role in modulating hemispheric functions involved in figurative language processing.

1.4. The current study

The previous studies reviewed above indicate that research in figurative language comprehension should consider a number of important variables, such as novelty of the stimulus, complexity of the stimulus, task difficulty, and semantic transparency of figurative expressions. The current study was designed to address these issues by testing Chinese idiom processing using the fMRI technique. The study of Chinese idioms from a neurocognitive perspective is highly significant, given their popularity and prominent characteristics as described below, but so far there has been no published fMRI study in this regard.ⁱ

Idioms are a distinct cultural feature of the Chinese language because of their pervasiveness in daily language use in Chinese and their richness in cultural and historic background knowledge, compared with idioms in other languages. The Chinese language has a large set of idioms due to the rich socio-cultural history of the language; the Complete Dictionary of Chinese Idioms (Wang, 2008) contains 18,000 Chinese idioms. Many of these idioms are based on historical or literary works, such as plays, legendary stories, or novels.ⁱⁱ Idioms also have a long history in Chinese, with some having existed for well over 2,000 years (most educated people today can

still read historical records written 2,000 years ago, for example, by Confucius).

Idioms are frequently used in ordinary Chinese speech and writings, since they usually deliver a complex meaning succinctly and vividly (Wang, 1990), and more than 90% of Chinese idioms consist of only four written characters (corresponding to spoken monosyllables) according to a corpus analysis (Lu, 1987).

Because many of modern-day Chinese idioms were developed in Classical Chinese, they typically have a different grammatical structure from the grammatical structures of regular phrases or sentences in Modern Chinese (see Jiao et al., 2011; Wang, 1990). By contrast, the grammatical construction of idioms in European languages usually resembles regular phrase constructions and can also undergo syntactic operations (e.g., passive voicing, topicalization, quantification, tense marking, and insertion; Cacciari and Glucksberg, 1994; Cacciari, 2014). For example, the idiom “*kick the bucket*” has the same grammatical structure as the phrase “*kick the ball*”. A minor change in the grammatical structure of Chinese idioms, however, will render them non-idiomatic (Liu et al., 2010). Because of these features of Chinese idioms, we hypothesize that the understanding of Chinese idioms involves little access to the constituent literal meanings, and hence weak selection or inhibition among the competing literal versus figurative meanings, in contrast to idioms in European languages. Idiom processing in European languages, as pointed out by Bohrn et al. (2012), among others, usually involves the selection and inhibition of multiple competing meanings, which is likely to lead to stronger engagement of the bilateral prefrontal cortex than does the processing of literal language.

In this study, we investigate the hemispheric mechanisms in the processing of Chinese idioms by manipulating idiom transparency at two different levels, matching the complexity of stimulus, and using familiar idioms or phrases without sentential

context. Given the issue of task difficulty as discussed before, we presented both idioms and literal phrases to participants with a non-semantic task - a font judgment task (see *Materials and Methods* for details). This type of non-linguistic visual feature detection task has been used in previous literature to investigate the cerebral correlates of implicit and automatic reading (see Brunswick et al., 1999; Price et al., 1996). For example, Brunswick et al. (1999) compared the detection of letter ascender (e.g., b, l) to the explicit task of word reading aloud, and found the former could also activate the classical language areas, including inferior frontal and superior and posterior temporal regions, which echoed the claim that visually presented words, in typical adult skilled readers, activate semantic processes even when the intention is not to read (Macleod, 1991; Neely, 1991). Considering that our stimuli are familiar to participants as shown by a rating task (see *Methods and Material*), we assume that the task of font judgment in the present study will involve automatic access of meaning in the idioms and literal phrases, while at the same time minimizing the involvement of meaning inhibition, selection, and decision-making, thereby reducing any differences in task demands for idioms versus literal phrases.

In order to investigate the contribution of transparency of idioms to hemispheric specialization, we compared opaque and transparent idioms with literal phrases. The idiomatic meaning of opaque idioms is very distant from the literal meaning of their constituents, and usually requires the participant's socio-cultural knowledge to access its meaning (see footnote ii for the example 叶公好龙 *ye gong hao long*). By contrast, transparent idioms, such as 装聋作哑 (*zhuang long zuo ya*), require less socio-cultural knowledge for understanding because the figurative meaning is more closely related to the literal meaning (e.g., 装聋作哑 *zhuang long zuo ya* has the literal meaning that a person pretends to be dumb and deaf, and the figurative

meaning that a person knows the truth but pretends not knowing anything). Finally, non-idiomatic literal phrases matched in word length (such as 跳下悬崖, *tiao xia xuan ya*, “jump off a cliff”) were also included in this study to serve as controls. In order to have an objective measure of the transparency of each stimulus, we asked a separate group of undergraduate students to rate the semantic distance between the figurative and the literal meaning, which confirmed a graded semantic distance from opaque idioms to transparent idioms to literal phrases (see *Materials and Methods*).

In the current study we highlighted the role of semantic transparency of idioms, while controlling for novelty (by using highly familiar phrases), complexity (by using phrases isolated from sentential context) and task demands (by using a non-semantic task). With this design, we intend to clarify the involvement of the RH vs. the LH during idiom comprehension, compared to non-idiomatic phrases. On the basis of previous findings, we make two main predictions in the current study. The first prediction focuses on whether the RH will be involved during idiom comprehension. In this study, all idioms (transparent and opaque idioms) are conventional idioms widely used in daily life, whereas the figurative meaning is more salient than the literal meaning. According to the graded salience hypothesis (Giora, 1997, 2003, 2007), only the LH will be activated during the comprehension of these popular and salient idioms. Thus, the idioms and the non-idiomatic phrases would elicit similar activation in LH areas, including IFG, ITG, MTG, and AG, and PCu (e.g., Bottini et al., 1994). By contrast, according to the fine-coarse semantic coding theory (Beeman, 1998; Jung-Beeman, 2005), the RH will be uniquely activated during idiom comprehension, because the idioms contain broad semantic information and require coarse semantic processing. Thus, the contrast between the idioms and the non-idiomatic phrases would indicate stronger RH effects. Additionally, the

conjunction between the two types of idioms may demonstrate significant bilateral activation, including the left frontal-temporal-parietal areas and right IFG, right ITG and MTG; whereas the conjunction between idiom and non-idiomatic phrases would indicate significant activation mainly in the left frontal-temporal-parietal areas.

The second prediction focuses on the semantic transparency of the idioms. The fine-coarse semantic coding theory suggests that RH is responsible for establishing relations between weak and dispersed semantic information, organizing pragmatic information, and reinterpreting language stimuli (Beeman, 1998; Beeman & Chiarello, 1998; Jung-Beeman, 2005). According to this theory, graded, decreasing RH effects should be found in the opaque idioms, transparent idioms, and non-idiomatic literal phrases (in that order). This is because the figurative meaning in the opaque idioms is more distant to the literal meaning than that in the transparent idioms, and moreover, opaque idioms usually contains rich socio-cultural knowledge and much broader semantic information than the other two conditions and requires the RH to organize the information. The non-idiomatic literal phrases do not contain any figurative meaning and should have no or minimal RH effects. Thus, the contrast between opaque and transparent idioms would show stronger RH effects, and the contrast between transparent idioms and literal phrases would also show stronger RH activation. With respect to specific brain regions of interest (ROIs), the ROI analysis will show a graded decreasing activation pattern in the RH across opaque idioms, transparent idioms, and non-idiomatic literal phrases. Finally, a regression analysis with the semantic distance for each idiom or non-idiomatic phrase included as an item-wise regressor will examine the relationship between the brain activations and the transparency of stimuli, and the RH frontal, temporal and/or parietal cortices could indicate significant regression effects as the fine-coarse coding theory suggests. The

graded salience hypothesis predicts that no difference among the three types of stimuli will be observed in the RH, because they are very familiar to the participants according to the subjective ratings (see Materials for details) and will be mainly processed by the LH.

2 Materials and Methods

2.1 Participants

Twenty healthy adult native speakers of Chinese (10 males, 20-25 years old, mean age = 21.7 years) from Beijing Normal University served as participants for this study and were paid for their participation. All were right-handed according to a modified Chinese version of the Edinburgh Handedness Inventory (Oldfield, 1971), and reported normal or corrected to normal vision. None had been diagnosed with any neurological or psychiatric disorder. All participants knew Chinese idioms well, as assessed by a separate test in which they completed an idiom cloze test. The idiom cloze test consisted of 36 four-character idioms (18 opaque idioms and 18 transparent idioms) that were not used in the formal experiment with one character missing in each idiom. The position of the missed character and the order of idiom types were pseudo-randomized in the test, and all participants achieved 90% or above accuracy in filling in the missing character. Data from one participant were excluded from analysis due to excessive head movements during scanning and a low overall accuracy (70%) on the in-scanner task. The study was approved by the local institutional review board and written informed consent was obtained from each participant before the experiment.

2.2 Materials

One hundred commonly used opaque idioms and 100 transparent idioms (all in

the form of four characters) were first selected from the Chinese Idiom Dictionary (Yu and Sun, 2004). Another 100 non-idiomatic four-character literal phrases were extracted from a text corpus (Yu et al., 2002). For each idiom or non-idiomatic phrase, a separate group of 30 native Chinese speakers who did not take part in the imaging experiment rated on a 1-7 Likert scale with regard to (1) familiarity with the idiom or non-idiomatic phrase (1 = totally unfamiliar; 7 = very familiar), (2) status of idiom (1 = Yes, it's an idiom, 0 = No, it's not an idiom), and (3) semantic distance between the figurative meaning and the literal meaning for the “yes” items in (2) (1 = very close, 7 = very distant). Frequency and visual complexity of each stimulus were also calculated. The frequency of each item was calculated according to the CCL Chinese Corpus (Center for Chinese Linguistics, Peking University; see Yu et al., 2002), which contains 4.77 hundred million characters. The visual complexity was defined as the total number of strokes of the four characters for each idiom or non-idiomatic phrase.

The final experimental stimuli included: (1) 48 opaque idioms, in which the figurative meaning was distant from the literal meaning, and significant socio-cultural knowledge is needed for figurative meaning comprehension, such as 叶公好龙 (*ye gong hao long*; literal meaning: *Mr. Ye loves dragons*; see footnote ii for its figurative meaning); (2) 48 transparent idioms, in which the distance between figurative meaning and literal meaning is relatively close, and hence little socio-cultural knowledge is required for accessing the figurative meaning, such as 装聋作哑 (*zhuang long zuo ya*; literal meaning: *pretend to be deaf and dumb*; figurative meaning: *pretend to be ignorant*); and (3) 48 four-character non-idiomatic literal phrases, which have no figurative meaning, such as 跳下悬崖 (*tiao xia xuan ya*; meaning: *jump off a cliff*).

The characteristics of each type of phrases ⁱⁱⁱ are presented in Table 1. The

rating results indicated that the status between idioms and non-idiomatic phrases was sufficiently different: both opaque and transparent idioms were rated close to 1, significantly higher than non-idiomatic phrases which were rated near 0 (both $ps < 0.001$). In addition, the acceptance proportion of opaque idioms was still higher than that of transparent idioms ($p < 0.001$), indicating the opaque idioms were more consistently accepted as idioms than the transparent ones. For the semantic distance, the rating results showed a clear graded effect across the three conditions ($F(2, 141) = 776.54, p < 0.001$), i.e., the ratings of two types of idioms were significantly higher than for the non-idiomatic phrases (both $ps < 0.001$), and the rating of the opaque idioms was higher than for the transparent idioms ($p < 0.001$). All three types of stimuli had very high familiarity rating scores (above 6 out of 7), indicating that people commonly use these expressions. Statistically, the non-idiomatic phrases had higher familiarity than both two types of idioms (both $ps < 0.001$), but there was no difference between the two types of idioms ($p > 0.5$). In addition, the three types of stimuli have similar frequency and stroke numbers (both $Fs < 1$). To assess inter-rater reliability (IRR), a two-way mixed, consistency, average-measures intra-class correlation (ICC) (McGraw & Wong, 1996) was calculated to evaluate the degree to which raters were consistent in their ratings of semantic distance across the three types of phrases. An ICC of 0.95, which was in the excellent range as suggested by Cicchetti (1994), indicated that raters had a high degree of agreement. Semantic distance ratings were therefore deemed to be suitable for testing hypotheses about semantic transparency.

The 144 stimulus items were divided into two lists, and each included 72 phrases (24 opaque idioms, 24 transparent idioms, and 24 non-idiomatic phrases). Each participant was presented with only one of the two lists during the fMRI experiment. The order of the three types of phrases was pseudorandomized to ensure that no more than three items of the same stimulus type appeared in succession during the scanning phase.

In addition to linguistic stimuli, participants were also presented with “#” symbols in separate blocks, which served as a baseline for language processing. Four “#” symbols (i.e., “####”) instead of four characters were shown each time.

Insert Table 1 about here

2.3 Experimental task and procedure

The functional MRI scanning phase consisted of four runs; each run included one experimental block and one baseline block and lasted 5 min 30 sec. In each experimental block, 18 phrases including 6 opaque idioms, 6 transparent idioms and 6 non-idiomatic phrases were presented pseudo-randomly. In each baseline block, four “#” symbols were presented 18 times. Each trial started with a fixation cross centered on the screen, which lasted for 300 ms; after a blank screen of 200 ms, a phrase or “#” symbols were shown for 1500 ms, followed by a blank of 1500 ms. The inter-trial-interval was jittered between 500 ms to 11000 ms (mean = 4500 ms). Participants were asked to press a button with one hand if they saw an italicized character (in experimental blocks) or an italicized symbol (in baseline blocks) and press another button with the other hand if they did not see an italicized character or

symbol, with assignment of hands counterbalanced between participants. In experimental blocks, half of the phrases of each type had one italicized character while the other half did not. The position of the italicized character in a phrase was evenly distributed among the four characters. In baseline blocks, half of the symbols contain an italicized “#”, which were also evenly distributed on the first, second, third and fourth position, and the other half did not contain any italicized symbol. The order of the baseline block and the experimental block within a run was counterbalanced across four runs, such that the experimental block occurred before the baseline block in two of four runs and the baseline block occurred before the experimental block in the other two runs.

Before the formal experiment, there was a practice session, during which participants made the same font judgments on another set of stimuli including idiomatic and non-idiomatic phrases that were not used in the in-scanner task. After scanning, participants were asked to interpret each idiom orally to the experimenter. Their answers were scored as either correct (1) or incorrect (0) based on the standard interpretations in the Chinese Idiom Dictionary (Yu and Sun, 2004) and analyzed for accuracy of interpretation (see the Results section).

2.4 Functional MRI acquisition

Imaging data were collected from a 3-T Siemens Magnetom Trio Scanner at the Imaging Center for Brain Research, Beijing Normal University. A gradient-echo, echo planar imaging (EPI) sequence was used to acquire the fMRI functional images (32 slices), with the following parameters: TR = 2000 ms, TE = 30 ms, FA = 90°, FOV = 200×200 mm², matrix = 64×64, thickness = 4 mm, inter-slice gap = 0.8 mm, voxel size = 3.125×3.125×4.8 mm³. High-resolution anatomical images (128 slices) of the entire brain were obtained by a MPRAGE sequence after functional images

were acquired, with the following parameters: 128 sagittal slices, TR = 2530 ms, TE = 3.39 ms, FA=7°, FOV = 256×256 mm², matrix = 256×256, thickness = 1.33 mm.

2.5 Data analysis

We preprocessed and statistically analyzed the imaging data with AFNI (Cox, 1996). The first four scans were discarded to minimize the influence of inhomogeneities in the magnetic field. A six-parameter rigid-body transformation was used to align all volumes to the last volume to correct head motion of the functional images after slice timing correction (Cox and Jesmanowicz, 1999). Individual functional images were coregistered with corresponding structural images, and then normalized to standard Talairach and Tournoux (1988) space and resampled to 3×3×3 mm³ voxel. Functional images were spatially smoothed with a 4-mm FWHM Gaussian kernel.

The preprocessed images were then submitted to individual general linear model GLM-based analysis to estimate the beta coefficient and statistical t-maps in each condition for each participant.

At group level, results were corrected for multiple comparisons at cluster level $p < .05$ using 3dClusterSim (<http://afni.nimh.nih.gov/>), by running Monte Carlo simulations (10,000 permutations) with the averaged blur estimates of the residuals across 19 subjects as the FWHM measurements in each of the x, y, and z dimensions and a 2-sided testing at voxel level, as suggested by the program. Group activation maps for each experimental condition relative to baseline condition were created through contrasting beta coefficient, and thresholded at $t > 3.909$ ($p < 0.001$), cluster size > 14 voxels (378 mm³), corrected to cluster $p < 0.05$. The spatial maps of planned comparisons between experimental conditions were thresholded at $t > 2.553$ ($p < 0.02$), cluster size > 63 voxels (volume ≥ 1701 mm³), achieving cluster-level $p < 0.05$,

as in Desai et al. (2010). After that, we performed two conjunction analyses to find the common regions for both idioms and non-idiomatic phrases and the common regions for transparent idioms and opaque idioms based on the three thresholded activation maps for each experimental condition compared with baseline, and only clusters larger than 10 voxels (volume $\geq 270 \text{ mm}^3$) were reported.

Previous studies using other languages and tasks reported the differences in the processing figurative and non-figurative language in bilateral fronto-parietal regions (Lauro et al., 2008; Zempleni et al., 2007). To examine whether there was any other meaningful difference among conditions that was not captured by the whole-brain analysis given the large number of voxels, we conducted an ROI analysis and focus on bilateral frontal and parietal areas are focused in the analysis. The exact ROIs were defined through the conjunction analyses: three clusters including left IFG/MFG, left and right SPL/PCu which were activated for all three experimental conditions, and two clusters including right IFG/MFG and right SPL/PCu (next to that area activated for all three experimental conditions) which were only activated for the two types of idioms under the applied threshold (see Table 4). For each participant and for each ROI, the mean beta values in each ROI for each experimental condition relative to the baseline condition were extracted with activated clusters as masks. Differences between every two conditions (i. e., opaque idioms vs. non-idiomatic phrases, transparent idioms vs. non-idiomatic phrases, opaque idioms vs. transparent idioms) were examined using planned *t*-test. Uncorrected *p* values were reported, with *p* values smaller than 0.017 (i.e., 0.05/3, corrected for familywise error rate using the Bonferroni correction) treated as significant.

Finally, to better capture the relationship between the brain activations and the semantic transparency of stimuli, the value from the semantic distance ratings for

each idiom or non-idiomatic phrase was included as an item-wise regressor in a separate individual analysis for each preprocessed image along with the six-parameter rigid-body transformations. Beta values from the analysis reflect how brain activation in each voxel is modulated proportionally by the change of semantic distance. The group map for modulation effects of semantic distance was contrasted against a constant value of 0, corrected to cluster $p < .05$ using the same threshold in the contrast analysis.

3 Results

3.1 Behavioral Data

The accuracy from the font judgment task across the three test conditions was all very high and similar to each other (opaque idioms: 95.7%; transparent idioms: 96.8% and non-idiomatic phrases: 96.1%), which indicated that the participants concentrated on the task during scanning and they performed the task (i.e., detecting italic characters or symbols) successfully. The average reaction times of the three types of stimuli were also similar (opaque idioms = 875 ms, transparent idioms = 866 ms, and non-idiomatic phrases = 847 ms). Repeated-measures ANOVA revealed that neither accuracy nor reaction time showed any significant difference across the three types of phrases ($ps > 0.1$), suggesting similar task difficulty across the conditions and, hence that any brain activation differences could not be attributed to task difficulty.

Analysis of the post-experiment oral interpretation showed that the accuracy for transparent idioms (95.4%) was significantly higher than that for opaque idioms (85.4%) ($t = 3.89$, $p < 0.01$), indicating that participants had more difficulty when explicitly reporting the meanings of opaque idioms even though the opaque idioms were rated as equally familiar as the transparent idioms.

3.2 Imaging Data

3.2.1 Group activation and contrast analyses

Table 2A-C presents group activations, which indicate activation clusters for each of the three experimental conditions relative to the baseline condition. The two types of idioms and the non-idiomatic phrases elicited extensive activations across a wide brain network. All three types of phrases evoked strong activations in the bilateral IFG and MFG (BA 45/46/9), insula (BA 13), fusiform gyrus (FG, BA 19/37), and SPL, PCu and AG (BA 7/19/39), indicating that bilateral brain areas were involved in the processing of idioms and non-idiomatic phrases when compared with baseline.

Insert Table 2A about here

Insert Table 2B about here

Insert Table 2C about here

Insert Figure 1 about here

To identify brain areas that showed different activation for different types of phrases under the font judgment task, four planned comparisons were conducted (see Table 3 and Figure 1).

Idioms versus non-idioms. First, we combined the opaque and transparent idioms together and then compared them with non-idioms. Brain areas that were more

activated for idioms included the right SPL/PCu (BA 7/19) and left lingual gyrus (LG)/FG/middle occipital gyrus (MOG) (BA 18/19), while there was no area that was found to be more activated for non-idiomatic phrases. Second, when comparing opaque idioms with non-idioms, again two clusters were found to be more activated for opaque idioms: the SPL/PCu (BA 7) which extending to right supramarginal gyrus (SMG, BA 40) and postcentral gyrus (BA 3) and the left LG/FG/MOG (BA 18/19), but no region was found to be more activated for non-idioms. Third, when transparent idioms were compared with non-idioms, we found that only the left SMG (BA 40) showed a higher activation for non-idiomatic phrases. In addition, there was a cluster in right SPL/PCu ((29, -64, 41), $t_{\max} = 3.413$) showing stronger activations for transparent idioms than for non-idioms, though the cluster did not survive the threshold because of its small volume size (13 voxels, 351 mm³). Together, all three comparisons indicated stronger activations in the right SPL/PCu for idioms, which suggests specialized roles for these brain areas during Chinese idioms processing.

Opaque versus transparent idioms. Comparison between the two types of idioms showed significantly more activations in several brain areas for opaque than for transparent idioms, including the right SPL (BA 7), and other areas like the right precentral and postcentral gyrus (BA 3/2/4), left SMG (BA 40), and left cerebellum. No area was found to be more activated for transparent than for opaque idioms.

 Insert Table 3 about here

3.2.2 Conjunction analyses

Based on group activation maps for each experimental condition relative to the baseline condition, two conjunction analyses were conducted to identify areas that are

common to both idioms and non-idioms and those common to both types of idioms only. As shown in Figure 2, bilateral regions including FG (BA 36/37/19/18), medial frontal gyrus (BA 6) and SPL/PCu (BA7/19) were commonly activated for all three experimental conditions (idioms and non-idioms), and there were more extended activations in the LH than in the RH. In addition, common regions for all three conditions also included the left IFG/MFG (BA 9/46/45/10) and the right cingulate gyrus (BA 32). The second conjunction analysis focused on regions activated for idioms only, and it showed activations mainly in the right brain regions, including the right IFG/MFG (BA 9) and right SPL/PCu (BA 7/19). In the LH, common activations for idioms were also observed in the FG and MOG (BA 18/19).

Insert Figure 2 about here

3.2.3 ROI analyses

To estimate the involvement of common regions for the comprehension of all stimulus types, five regions in the frontal and the parietal lobes were defined as ROIs (see Table 4; see rationale in section 2.5). Statistical tests revealed that there was no activation difference in the left IFG/MFG or left SPL/PCu ($ps > .45$), suggesting similar involvement of left hemisphere in the processing of idioms and non-idioms (see Figure 2). In the right SPL/PCu ROI that were activated across all three experimental conditions (in red), both the activation for opaque idioms and that for transparent idioms were stronger than that for non-idiomatic phrases areas ($t(18) = 2.70, p = .015$ and $t(18) = 2.60, p = .018$, respectively), but the difference between the two types of idioms was not significant ($t(18) = 0.49, p = .633$). In the other cluster in the right SPL/PCu (in yellow), which was activated for idioms only, activation for

opaque idioms was stronger than that for non-idioms ($t(18) = 2.71, p = .014$), with transparent idioms in between and not significantly different from either opaque idioms ($t(18) = -0.63, p = .539$) or non-idioms ($t(18) = 1.84, p = .082$). Finally, the differences between conditions in the right IFG/MFG were not significant ($ps > .30$).

 Insert Table 4 about here

3.2.4 Amplitude modulated regression analysis

The modulation effect of semantic transparency of the phrases on brain activation was assessed in a separate model where semantic distance between the figurative meaning and the literal meaning of the constituent characters was treated as a continuous variable and included as an item-wise regressor. As seen in Figure 3 and Table 5, the activation extent of the three regions was positively correlated with the semantic distance, including the left LG/FG/MOG (BA 18/19), the left parahippocampal gyrus (BA 36/20), and most importantly, the right AG/SPL/PCu (BA 39/7). These regression-based analyses were consistent with the previous analyses and further supported the role of right AG/SPL/PCu during idiom processing. Furthermore, the modulation effect observed in the right AG/SPL/PCu and left FG cannot be explained by imageability^{iv} of phrases given that the activation in the two clusters were still significantly modulated by semantic distance even when imageability was included as an additional item-wise regressor (see the Supplementary Material for more details about the methods and results associated with imageability).

Insert Figure 3 about here

Insert Table 5 about here

4. General Discussion

4.1 Role of LH vs. RH in Chinese idiom processing

What role does the right hemisphere (RH) play in figurative language comprehension as compared with the left hemisphere (LH)? A large literature on figurative language processing has been devoted to this question, but answers remain elusive in light of the differential involvement of both hemispheres reported in the literature and the corresponding theoretical hypotheses. As we discussed in the Introduction, earlier theories suggest that the RH plays a unique role in non-literal meaning interpretation, but more recent studies have found data inconsistent with this suggestion. The current study compared brain activations for Chinese idioms (transparent and opaque) and non-idioms (literal phrases) in a non-semantic task. Both figurative and non-figurative stimuli led to strong activations in language regions, such as the left IFG and AG. This pattern is consistent with findings from other word or phrase processing studies using implicit semantic tasks that have shown automatic semantic processing with this type of tasks (e.g. Brunswick et al., 1999; Kang et al., 1999; Price et al., 1996). Overall, we observed that the idioms and non-idioms elicited activation in overlapping brain regions in both the left and right hemispheres. However, the patterns from whole-brain contrasts and conjunction analyses as well as ROI analyses suggest that Chinese idiom comprehension additionally requires

stronger involvement of the right brain regions, particularly areas in the parietal cortex, including the PCu and SPL. The modulation analyses further indicate negative correlations between the transparency of the stimuli and the level of activation in the right AG, PCu and SPL, suggesting that more opaque idioms may induce stronger activations in these regions.

One critical issue that has been a matter of contention in the literature is whether studies showing more RH involvement also involve greater task demands (e.g. Grady et al., 1998) as discussed earlier, and the hypothesis is that RH activation is due perhaps to higher task difficulties rather than figurative language processing per se (see Lee and Dapretto, 2006; Rapp et al., 2004; Stringaris et al., 2007). For example, Bottini et al. (1994) observed additional RH involvement during metaphor processing compared with the processing of literal sentences, but the complexity of the sentences in the two conditions were not well-matched, and subjects made significantly more mistakes interpreting metaphoric compared to literal sentences (see also reviews in Kasparian, 2013; Stringaris et al., 2007). In contrast, Lee and Dapretto (2006) found no selective involvement of RH (and even greater LH) involvement for metaphorical processing when the stimulus properties and task difficulty were matched. A similar data pattern was also found in Rapp et al. (2007). In the present study we employed a character-form (font) judgment task in which participants did not need to actively pay attention to the meaning of the stimuli, so that the semantic processing differences between idioms and non-idioms did not involve different task difficulties. Moreover, the idioms and non-idioms were matched orthographically (visual complexity, and location of italic characters) and lexically (frequency and length), and the behavioral results showed no group differences between the idiom and non-idiom conditions. Therefore, it is not likely that the additional activations in the right brain regions for

opaque and transparent idioms observed in our study can be attributed to increased task difficulty.

4.2 Role of precuneus and angular gyrus in knowledge integration

Is the involvement of the RH for Chinese idioms as demonstrated in our study due to meaning selection or inhibition? Explicit tasks in previous studies of idiom processing usually require meaning selection and inhibition, because idiom processing in Western languages usually involves a stage at which literal meanings are initially activated (see Introduction). Results from those studies indicate that semantic selection is an essential process in idiom processing, during which the bilateral IFG plays an important role (see Lauro et al., 2008). The present study, in contrast to previous studies, uses Chinese idioms with highly accessible figurative meaning and weak literal meaning, and with a task in which participants are not required to make a semantic selection or judgment. Thus, the particular RH activations in AG/PCu areas seen in the processing of Chinese idioms are unlikely due to the effect of semantic selection. Instead, these areas might reflect processes of semantic retrieval or integration of relative background knowledge associated with the Chinese idioms when the figurative meaning is accessed, which brings us to the next point.

The role of the right AG/PCu in figurative meaning processing has rarely been reported in idiom or metaphor studies on healthy participants, with the exception of Bottini et al. (1994) and Mashal et al. (2005). As discussed earlier, Bottini et al. (1994) used sentence stimuli with complex syntactic and /or semantic information, and observed that metaphorical sentences elicited similar activations as literal sentences in the LH including the left PCu and IFG. Furthermore, metaphorical sentences additionally elicited activation in several areas in the RH, particularly in the right PCu.

Data from an fMRI study by Mashal et al. (2005) indicated that the right PCu plays an important role in processing novel metaphors but not in processing familiar metaphors. Taken together, these data patterns and other previous studies suggest that the PCu is highly involved in episodic memory retrieval (e.g., Cabeza and Nyberg, 2000; Lundstrom et al., 2005; see review Hutchinson et al., 2009) or mental imagery recollection (e.g., Fletcher et al., 1995; Shallice et al., 1994). A similar function of episodic memory retrieval has also been found in the adjacent AG (Vilberg and Rugg, 2008). Previous studies, however, have found that the AG, especially in the RH, is consistently involved in semantic processing. For example, Binder et al. (2009) performed a meta-analysis of 120 functional neuroimaging studies, and found that a consistent semantic activation is located in the left AG, with a less strong but stable effect in the right AG. They suggested that the AG very likely plays a role in complex knowledge retrieval and information integration (Binder et al., 2009). In general, the AG is implicated in building event representations and in interpreting pragmatics such as metaphors, ironies, and sarcasms (Binder and Desai, 2011; Yarkoni et al., 2008).

Our contrast analyses showed that both types of idioms had stronger activations in the right PCu than non-idioms, and the ROI analyses indicated similar patterns in the right PCu. The modulation-based regression analysis further confirmed that the involvement of right AG/PCu negatively correlated with the semantic transparency of the stimuli (i.e., the less transparent idioms elicit stronger activation). Given these findings, we speculate that the right AG/PCu may be involved in the retrieval or integration of background knowledge for semantic access of idioms. As discussed in the Introduction, a high degree of extra background knowledge is needed for accessing figurative meaning, particular for the opaque idioms, and particularly for processing Chinese opaque idioms that involve a high degree of socio-cultural and

historic background knowledge.

Right superior parietal lobe (SPL) was also shown to be significantly correlated with idiom processing in our present study. This pattern is less easily interpretable in terms of figurative language comprehension. This brain region is typically thought to be involved in visuo-spatial attention processing (Kanai et al., 2010), mental spatial rotation (Wolbers et al., 2003), ambiguous decision-making (Krain et al., 2006), and also working memory (Stretton et al., 2012). Hence, one possible explanation might be that the attention network, which includes the right SPL, and possibly the PCu, was differentiated by types of language phrases, i.e., opaque idioms might require from the comprehenders more attentional resource to integrate more information .

4.3 Role of background knowledge for Chinese idiom processing

Although we believe that socio-cultural background knowledge to be a very important contributor to the understanding of opaque idioms in any language, the Chinese opaque idioms are distinctly different from those in Indo-European languages. While the example ‘kick the bucket’ illustrates the possibility of a direct access/retrieval of meaning from semantic memory (‘being dead’), this is not the case with a very large number of opaque idioms in the Chinese language, because of the rich knowledge embedded in Chinese idioms that are based on legendary stories, historical records, or classic novels. These idioms, such as the example 叶公好龙 *ye gong hao long* (“Mr. Ye loves dragon”; see footnote ii), cannot be understood if the background knowledge is not properly encoded or retrieved in the first place.

In an effort to clarify what we mean by the richness of socio-cultural and historic background knowledge for Chinese idioms, as compared with idioms in other languages, we searched 2,086 frequently used Chinese idioms from a well-established

and widely used research database, the Language Corpus System of Modern Chinese Studies (Sun et al., 1997), and classified these idioms into two categories: (a) opaque idioms, such as the ones used in our experimental stimuli, (b) transparent or semi-transparent idioms, which were similar to the transparent idioms in our experiment. The analyses indicated that out of the 2,068 idioms, more than half (60%, 1,245 items) belong to category (a), whereas category (b) had 40% (823 items). In addition, many of the category (a) items are idioms that are based on historical texts or stories, according to our further analyses of published dictionaries of idioms available in Chinese. These include *A Complete Dictionary of Chinese Idioms* (Wang, 2008), *A Dictionary of Frequent Idioms* (2011; Fudan University Press), *A Dictionary of Stories of Chinese Idioms* (Zhang and Yu, 2001), and *Abridged Dictionary of Stories of Chinese Idioms* (Wu, 2002). The number of idioms listed in Zhang and Yu (2001) was 6,000, suggesting that a large number of idioms are based on historical or literary works, such as plays, legendary stories, or novels. That is, given the *Complete Dictionary of Chinese Idioms* that contained 18,000 items, we can safely assume that about 1/3 of all idioms are story-based idioms. These data provide a glimpse of the extent to which Chinese idioms have evolved out of the long history of the language, and the degree to which correct idiom usage today draws on background sociocultural knowledge.

Given the above situation, merely remembering the meaning of the idiom without the relevant sociocultural knowledge might work only for a small portion of Chinese idioms with only a shallow understanding. Indeed, native Chinese speaker

learn opaque idioms starting from elementary school through the introduction of stories from their textbooks and idiom dictionaries (such as Wu, 2002 as mentioned above). Previous studies in the learning of Chinese idioms have found that students, when knowing the origins of idioms, can more readily figure out the figurative meanings and remember the idioms better (e.g., Boers, 2001). This characteristic of dependency on background or origin knowledge is thus likely to be particularly important for correctly understanding and using Chinese opaque idioms.

4.4 Role of other cortical regions and task demands in idiom processing

In contrast to the activation of the AG/PCu/SPL, our study has shown no specific effect of the bilateral IFG in the processing of idioms, as the comparison between idioms and non-idioms yields no significant difference. This pattern differs from the suggestion in the literature that the bilateral IFG plays an important role in figurative language processing, as summarized in the review of Bohrn et al. (2012). One possible explanation of this absence of IFG's role in Chinese idiom processing is that we used a non-semantic judgment task, and the task demand is relatively low in our experiment. Previous studies of figurative language processing have used mostly explicit tasks that place higher processing demand, including stimuli that were also more complex than ours, either of which could lead to increased frontal activation, especially in the RH (Schmidt et al., 2009). A number of previous studies have also suggested that the left IFG is related to the retrieval of semantic knowledge (Fiez, 1997; Friederici et al., 2000; Gabrieli et al., 1998). Other studies (Lauro et al., 2008; Thompson-Schill et al., 1997) propose that the left IFG is not related to the retrieval of semantic knowledge per se but rather the selection among competing alternatives

from semantic memory. These task-based cognitive demands may be responsible for the observed patterns in previous studies involving explicit semantic tasks; however, they would not be expected to contribute to the current study involving a non-semantic, font-judgment task.

The left temporo-occipital cortex, including the lingual gyrus, fusiform gyrus, and middle occipital gyrus, was found to be strongly activated or negatively correlated with the transparency of meaning, when literal phrases were contrasted with both types of idioms or with opaque idioms only, in both the contrast and the regression analyses. Previous research found that these temporo-occipital areas are involved during the visual and orthographic processing of Chinese, as demonstrated by Liu et al. (2008) and Wang et al. (2011), among others. Although all types of phrases were matched on visual features (e.g., number of stroke, length, and the ratio as well as the distribution of italicized characters) on the literal phrases and idioms, it is still possible that the idioms, especially the opaque idioms, could have attracted more attention to focus on the visual and orthographic features of the phrases. Studies have revealed that attention could enhance the activation of the visual word form area (VWFA) during the viewing of word stimuli (e.g., Xu et al., 2012). Another possible explanation is that the left temporo-occipital effects are related to the different semantic processes in literal phrases and idioms, because the three conditions have different semantic features (e.g., semantic distance). Previous studies have shown that these temporo-occipital areas are also involved in semantic-conceptual processing (Ghosh et al., 2010; Hinojosa et al., 2000), and eye-tracking research has also found that more fixations and longer gaze duration at the visual scenes when hearing figurative sentences compared to their literal counterparts (Singh and Mishra, 2010). Future research is needed to distinguish these two possibilities driving the

temporo-occipital involvement during idioms processing.

A final note regarding the percentage of idioms (67%) and that of the literal phrases (33%) in our stimuli cohort, which might lead one to suspect that participants might adopt some strategies when viewing the language stimuli. While we could not rule out this possibility, it is important to note the non-semantic font judgment task requires participants to pay attention to only to the surface features of the language stimuli. The percentages of the italicized items and the non-italicized items were the same (50% vs. 50%), and the italicized items were evenly distributed on the first, second, third and fourth position. This task and the design could minimize or reduce participants' possible strategies when they viewed the language stimuli. Future research could include a more balanced design with the same number of idioms and literal phrases.

In conclusion, findings from the processing of Chinese idioms as reported in this study provide neurocognitive evidence that both the LH and the RH are involved in idiom processing, although in different ways. Significantly, idioms engaged more activation than do non-idioms in the right parietal cortex, and moreover, the activation strength decreased as a function of semantic transparency of phrases. Clearly, this data pattern goes against the graded salience hypothesis that predicts the processing of familiar phrases mainly involves the LH and not the RH and. Hence, no activation difference would be expected to be observed across the three types of phrases in the RH, since they are very familiar to our participants (above 6 out of 7 as rated) and are also matched in terms of familiarity. By contrast, the patterns of RH activations in our study are largely consistent with the proposal of the theory by Beeman and Chiarello (1998), and Beeman (1998) and Jung-Beeman (2005), in that “coarse coding” provides a resource and backup for accessing figurative meanings, inferring the

speaker's intentions beyond the literal meaning, and achieving global coherence during discourse processing. These functions are crucial for the processing of idioms, especially for Chinese idioms in which the integration of various pragmatic, socio-cultural, and contextual meanings is mandatory. Our data suggest a potential right parietal hub (AG/PCu and SPL) in retrieving and integrating idioms in Chinese. This RH lateralized circuitry is complementary to the functions performed by the LH for basic semantic processing, which might be more important for setting up more fine-grained semantic associations for literal and non-literal meanings alike. This type of 'fine coding' makes it possible to generate the optimal interpretation of figurative language, and to integrate the central topic of discourse (Beeman, 1998; Beeman and Chiarello, 1998; Jung-Beeman 2005). Because our study uses a non-semantic task, our data further confirm that the two hemispheres play complementary roles and collaborate even when semantic processing is not explicitly required in the task. An important question that remains to be addressed in future research is whether this complementarity is specific to idiom processing, and how we can identify mechanisms underlying the different roles of the two hemispheres in language and cognition in general.

Acknowledgments

This work was supported by grants from Macquarie University Research Development Grant (MQRDG 9201401500) to JY, from Natural Science Foundation of China (31271082, 61373065, 81461130018) and from Beijing Municipal Science & Technology Commission (Z151100003915122) to HS and YL, from the National Science Foundation (BCS-1338946; BCS-1533625) to PL, from the Fund for Foreign Scholars in University Research and Teaching Programs (B07008) and the Fund for Humanities and Social Sciences Researcher Center under the Ministry of Education (08JJD740063) to PL and HS. We thank Angela Grant and Jennifer Legault for comments on an earlier draft of this manuscript.

References

- A Dictionary of Frequent Idioms. 2011. Shanghai, China: Fudan University Press.
- Beeman, M.J., 1998. Coarse semantic coding and discourse comprehension. In: Beeman, M., Chiarello, C. (Eds.), Right hemisphere language comprehension, perspectives from cognitive neuroscience. Mahwah, NJ: Erlbaum, pp. 255-284.
- Beeman, M.J., Chiarello, C., 1998. Complementary right- and left-hemisphere language comprehension. *Curr. Dir. Psychol. Sci.* 7, 2-8.
- Beeman, M., Friedman, R.B., Grafman, J., Perez, E., Diamond, S. and Lindsay, M.B., 1994. Summation priming and coarse semantic coding in the right hemisphere. *J. Cogn. Neurosci.* 6(1), 26–45.
- Binder, J.R., Desai, R.H., 2011. The neurobiology of semantic memory. *Trends Cogn. Sci.* 15, 527–536.
- Binder, J.R., Desai, R.H., Graves, W.W., Conant, L.L., 2009. Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cereb. Cortex* 19 (12), 2767–96.
- Boers, F., 2001. Remembering figurative idioms by hypothesizing about their origin. *Prospect* 16(3), 34-43.
- Bohrn, I.C., Altmann, U., Jacobs, A.M., 2012. Looking at the brains behind figurative language: A quantitative meta-analysis of neuroimaging studies on metaphor, idiom, and irony processing. *Neuropsychologia* 50 (11), 2669-2683.
- Bottini, G., Corcoran, R., Sterzi, R., Paulesu, E., Schenone, P., Scarpa, P., Frackowiak, R.S., Frith, C.D., 1994. The role of the right hemisphere in the interpretation of figurative aspects of language: A positron emission tomography activation study. *Brain* 117, 1241-1253.

- Brunswick, N., McCrory, E., Price, C.J., Firth, C.D., Firth, U., 1999. Explicit and implicit processing of words and pseudowords by adult developmental dyslexics. A search for Wernicke's Wortschatz? *Brain* 122, 1901-1917.
- Cabeza, R., Nyberg, L., 2000. Imaging cognition II: an empirical review of 275 PET and fMRI studies. *J. Cogn. Neurosci.* 12, 1–47.
- Cacciari, C., 2014. Processing multiword idiomatic strings: many words in one? *The Mental Lexicon* 9(2), 267-293.
- Cacciari, C., Glucksberg, S., (1994). Understanding figurative language. In M. A. Gernsbacher (Ed.), *Handbook of Psycholinguistics* (pp. 447–477). New York: Academic Press.
- Cicchetti, D.V., 1994. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychol. Assess.* 6(4), 284.
- Cox, R.W, Jesmanowicz, A., 1999. Real-time 3D image registration for functional MRI. *Magn. Reson. Med.* 42, 1014-1018.
- Cox, R.W., 1996. AFNI, software for analysis and visualization of functional magnetic resonance neuroimages. *Comput. Biomed. Res.* 29, 162–173.
- Desai, R.H., Binder, J.R., Conant, L.L., Seidenberg, M.S., 2010. Activation of sensory-motor areas in sentence comprehension. *Cereb. Cortex* 20, 4688–478.
- Faust, M., Mashal, N., 2007. The role of the right cerebral hemisphere in processing novel metaphoric expressions taken from poetry: A divided visual field study. *Neuropsychologia* 45 (4), 860-870.
- Faust, M., Weisper, S., 2000. Understanding metaphoric sentences in the two cerebral hemispheres. *Brain Cogn.* 43 (1-3), 186-191.

- Fiez, J.A., 1997. Phonology, semantics, and the role of the left inferior prefrontal cortex. *Hum. Brain Mapp.* 5, 79-83.
- Fletcher, P.C., Frith, C.D., Baker, S.C., Shallice, T., Frackowiak, R.S., Dolan, R.J., 1995. The mind's eye-precuneus activation in memory-related imagery. *NeuroImage* 2, 195–200.
- Friederici, A.D., Opitz, B., von Cramon, D.Y., 2000. Segregating semantic and syntactic processing. *Cereb. Cortex* 10, 698-705.
- Gabrieli, J.D.E., Poldrack, R.A., Desmond, J.E., 1998. The role of left prefrontal cortex in language and memory. *Proc. Nat. Acad. Sci. USA.* 95, 906-913.
- Gagnon, L., Goulet, P., Giroux, F., Joannette, Y., 2003. Processing of metaphoric and non-metaphoric alternative meanings of words after right-and left-hemispheric lesion. *Brain and Lang.* 87(2), 217-226.
- Ghosh, S., Basu, A., Kumaran, S.S. and Khushu, S., 2010. Functional mapping of language networks in the normal brain using a word-association task. *Indian J. Radiol. Imaging* 20(3), 182-187.
- Giora, R., 1997. Understanding figurative and literal language: The graded salience hypothesis. *Cogn. Linguist.* 8, 183-206.
- Giora, R., 2003. *On our mind: Salience, context and figurative language*. New York: Oxford University Press.
- Giora, R., 2007. Is metaphor special? *Brain Lang.* 100 (2), 111-114.
- Giora, R., Zaidel, E., Soroker, N., Batori, G., Kasher, A., 2000. Differential effects of right- and left-hemisphere damage on understanding sarcasm and metaphor. *Metaphor Symb.* 15(1–2), 63–83.

- Grady, C.L., Horwitz, B., Pietrini, P., Mentis, M.J., Ungerleider, L.G., Rapoport, S.I., Haxby, J.V., 1998. Effect of task difficulty on cerebral blood flow during perceptual matching of faces. *Hum. Brain Mapp.* 4, 227-239.
- Hinojosa, J.A., Martín-Loeches, M., Gómez-jarabo, G., Rubia, F.J., 2000. Common basal extrastriate areas for the semantic processing of words and pictures. *Clin. Neurophysiol.* 111(3), 552-560.
- Hutchinson, J.B., Uncapher, M.R., Wagner, A.D., 2009. Posterior parietal cortex and episodic retrieval: convergent and divergent effects of attention and memory. *Learn. Mem.* 16 (6), 343-356.
- Jiao, L., Kubler, C.C., Zhang, W., 2011. 500 Common Chinese Idioms: an Annotated Frequency Dictionary. London; New York: Routledge.
- Jung-Beeman, M., 2005. Bilateral brain processes for comprehending natural language. *Trends Cogn. Sci.* 9 (11), 512-518.
- Kacirik, N.A., Chiarello, C., 2007. Understanding metaphors: is the right hemisphere uniquely involved? *Brain Lang.* 100, 188–207.
- Kanai, R., Bahrami, B., Rees, G., 2010. Human parietal cortex structure predicts individual differences in perceptual rivalry. *Curr. Biol.* 20, 1626-1630
- Kang, A.M., Constable, R.T., Gore, J.C., Avrutin, S., 1999. An event-related fMRI study of implicit phrase-level syntactic and semantic processing. *Neuroimage* 10, 555–561.
- Kasparian, K., 2013. Hemispheric differences in figurative language processing: Contributions of neuroimaging methods and challenges in reconciling current empirical findings. *J. Neurolinguist.* 26 (1), 1-21.

- Kircher, T.T., Brammer, M., Andreu, N.T., Williams, S.C., McGuire, P.K., 2001. Engagement of right temporal cortex during linguistic context. *Neuropsychologia* 39, 798–809.
- Knutson, K.M., Wood, J.N., Grafman, J., 2004. Brain activation in processing temporal sequence: an fMRI study. *Neuroimage* 23, 1299–1307.
- Krain, A.L., Wilson, A.M., Arbuckle, R., Castellanos, F.X., Milham, M.P., 2006. Distinct neural mechanisms of risk and ambiguity: A meta-analysis of decision-making. *NeuroImage* 32, 477-484.
- Lauro, L.J.R., Tettamanti, M., Cappa, S.F., Papagno, C., 2008. Idiom comprehension: A prefrontal task? *Cereb. Cortex* 18, 162-170.
- Lee, S.S., Dapretto, M., 2006. Metaphorical vs. literal word meanings: fMRI evidence against a selective role of the right hemisphere. *Neuroimage* 26, 539-544.
- Liu, C., Zhang, W.T., Tang, Y.Y., Mai, X.Q., Chen, H.C., Tardif, T., Luo, Y.J., 2008. The visual word form area: evidence from an fMRI study of implicit processing of Chinese characters. *Neuroimage* 40 (3), 1350-1361.
- Liu, Y., Li, P., Shu, H., Zhang, Q., Chen, L., 2010. Structure and meaning in Chinese: An ERP study of idioms. *J. Neurolinguist.* 23(6), 615-630.
- Lu, Z.Q., 1987. Characteristics and variation in Chinese idioms. *Language Planning* 3, 25-27.
- Lundstrom, B.N., Ingvar, M., Petersson, K.M., 2005. The role of precuneus and left inferior frontal cortex during source memory episodic retrieval. *Neuroimage* 27 (4), 824-834
- MacLeod, C.M., 1991. Half a century of research on the Stroop effect: An integrative review. *Psychol. Bull.* 109, 163–203.

- Mashal, N., Faust, M., Hendler, T., 2005. The role of the right hemisphere in processing nonsalient metaphorical meanings: Application of principal components analysis to fMRI data. *Neuropsychologia* 43 (14), 2084-2100.
- Mashal, N., Faust, M., Hendler, T., Jung-Beeman, M., 2007. An fMRI investigation of the neural correlates underlying the processing of novel metaphoric expressions. *Brain Lang.* 100 (2), 115-126.
- Mashal, N., Faust, M., Hendler, T., Jung-Beeman, M., 2008. Hemispheric differences in processing the literal interpretation of idioms: Converging evidence from behavioral and fMRI studies. *Cortex* 44, 848-860.
- Mason, R.A., Just, M., 2004. How the brain processes causal inferences in text: A theoretical account of generation and integration component processes utilizing both cerebral hemispheres. *Psychol. Sci.* 15, 1–7.
- McGraw, K.O., Wong, S.P., 1996. Forming inferences about some intraclass correlation coefficients. *Psychol. Methods* 1(1), 30-46.
- Meyer, M., Friederici, A.D., von Cramon, D.Y., 2000. Neurocognition of auditory sentence comprehension: event related fMRI reveals sensitivity to syntactic violations and task demands. *Cogn. Brain Res.* 9, 19–33.
- Neely, J.H., 1991. Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner & G.W. Humphreys (Eds.), *Basic Processes in Reading: Visual Word Recognition*. Hillsdale, NJ: Erlbaum. pp. 264–336
- Oldfield, D.J., 1971. The assessment of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.

- Oliveri, M., Romero, L., Papagno, C., 2004. Left but not right temporal involvement in opaque idiom comprehension: A repetitive transcranial magnetic stimulation study. *J. Cogn. Neurosci.* 16, 848-855.
- Pobric, G., Mashal, N., Faust, M., Lavidor, M., 2008. The role of the right cerebral hemisphere in processing novel metaphoric expressions: a transcranial magnetic stimulation study. *J. Cogn. Neurosci.* 20 (1), 170-181.
- Price, C.J., Wise, R.J.S., Frackowiak, R.S.J., 1996. Demonstrating the implicit processing of visually presented words and pseudowords. *Cereb. Cortex* 6, 62-70.
- Proverbio, A.M., Crotti, N., Zani, A., Adorni, R., 2009. The role of left and right hemispheres in the comprehension of idiomatic language: an electrical neuroimaging study. *BMC Neurosci.* 10 (1), 116.
- Rapp, A.M., Leube, D.T., Erb, M., Grodd, W., Kircher, T.T., 2004. Neural correlates of metaphor processing. *Cognitive Brain Res.* 20 (3), 395-402.
- Rapp, A.M., Leube, D.T., Erb, M., Grodd, W., Kircher, T.T.J., 2007. Laterality in metaphor processing: Lack of evidence from functional magnetic resonance imaging for the right hemisphere theory. *Brain Lang.* 100, 142-149.
- Rapp, A.M., Mutschler, D.E., Erb, M., 2012. Where in the brain is nonliteral language? A coordinate-based meta-analysis of functional magnetic resonance imaging studies. *Neuroimage* 63 (1), 600-610.
- Rizzo, S., Sandrini, M., Papagno, C., 2007. The dorsolateral prefrontal cortex in idiom interpretation: An rTMS study. *Brain Res. Bull.* 71, 523–528.
- Shallice, T., Fletcher, P., Firth, C.D., Grasby, P., Frackowiak, R.S.J., Dolan, R.J., 1994. Brain regions associated with acquisition and retrieval of verbal episodic memory. *Nature* 368, 633 - 635.

- Schmidt, G.L., DeBuse, C.J., Seger, C.A., 2007. Right hemisphere metaphor processing? Characterizing the lateralization of semantic processes. *Brain Lang.* 100 (2), 127-141.
- Schmidt, G.L., Kranjec, A., Cardillo, E.R., Chatterjee, A., 2009. Beyond laterality: a critical assessment of research on the neural basis of metaphor. *J. Int. Neuropsych. Soc.* 16, 1–5.
- Singh, N., Mishra, R.K., 2010. Simulating motion in figurative language comprehension. *Open Neuroimag. J.* 4, 46–52.
- St. George, M., Kutas, M., Martinez, A., Sereno, M.I., 1999. Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain* 122, 1317–1325
- Stretton, J., Winston, G., Sidhu, M., Centeno, M., Vollmar, C., Bonelli, S., et al., 2012. Neural correlates of working memory in temporal lobe epilepsy: An fMRI study. *NeuroImage* 60(3), 1696-1703.
- Stringaris, A.K., Medford, N.C., Giampietro, V., Brammer, M.J., David, A.S., 2007. Deriving meaning: Distinct neural mechanisms for metaphoric, literal, and non-meaningful sentences. *Brain Lang.* 100 (2), 150-162.
- Sun, H.L., Huang, J.P., Sun, D.J., Li, D.J., Xing, H.B., 1997. Introduction to language corpus system of modern Chinese study. In M.Y. Hu (Ed.), *Paper Collection for the Fifth World Chinese Teaching Symposium*. Beijing: Peking University Publisher.
- Swinney, D. A., Cutler, A., 1979. The access and processing of idiomatic expressions. *J. Verb. Learn. Verb. Be.* 18, 523–534.

- Tabossi, P., Zardon, F., 1995. The activation of idiomatic meaning. In Everaert, M., van der Linden, E.J., Schenk, A. Schreuder, R. (Eds.). *Idioms: Structural and Psychological Perspectives*. New Jersey: Lawrence Erlbaum, pp. 273-282.
- Talairach, J., Tournoux, P., 1988. *Co-planar Stereotaxic Atlas of the Human Brain*. Stuttgart, Thieme.
- Thompson-Schill, S.L., D'Esposito, M., Aguirre, G.K., Farah, M.J., 1997. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: a reevaluation. *Proc. Nat. Acad. Sci. USA*. 94, 14792-14797.
- Uchiyama, H. T., Saito, D. N., Tanabe, H. C., Harada, T., Seki, A., Ohno, K., Koeda, T., Sadato, N., 2012. Distinction between the literal and intended meanings of sentences: A functional magnetic resonance imaging study of metaphor and sarcasm. *Cortex* 48 (5), 563-583.
- Van Lancker, D. Kempler, D., 1987. Comprehension of familiar phrases by left but not by right hemisphere damaged patients. *Brain Lang.* 32, 265–277.
- Vilberg, K.L., Rugg, M.D., 2008. Memory retrieval and the parietal cortex: A review of evidence from a dual-process perspective. *Neuropsychologia* 46, 1787–1799.
- Wang, L., 1990. Idiom and classical allusion. In L. Wang, *Collection of WangLi* (Vol. 11) (pp. 653-672). Shandong, China: Shandong Educational Press.
- Wang, T., 2008. *A Complete Dictionary of Chinese Idioms*. Shanghai, China: Shanghai Dictionary Press.
- Wang, X., Yang, J., Shu, H., Zevin, J.D., 2011. Left fusiform BOLD responses are inversely related to word-likeness in a one-back task. *Neuroimage* 55 (3), 1346-1356.
- Wolbers, T., Weiller, C., Buchel, C., 2003. Contralateral coding of imagined body parts in the superior parietal lobe. *Cereb. Cortex* 13(4), 392-399.

- Wu, B., 2002. Abridged Dictionary of Stories of Chinese Idioms. Hefei, China: Huangshan Press.
- Xu, G., Jiang, Y., Ma, L., Yang, Z., Weng, X., 2012. Similar spatial patterns of neural coding of category selectivity in FFA and VWFA under different attention conditions. *Neuropsychologia* 50, 862-868.
- Yang, J., 2014. The role of the right hemisphere in metaphor comprehension: A meta-analysis of functional magnetic resonance imaging studies. *Hum. Brain Mapp.* 35, 107-122.
- Yarkoni, T., Speer, N.K., Zacks, J.M., 2008. Neural substrates of narrative comprehension and memory. *Neuroimage* 41(4), 1408-1425.
- Yu, J.C., Sun, M.M., 2004. Chinese Idiom Dictionary. Beijing, China: The Commercial Press.
- Yu, S.W., Duan, H.M., Zhu, X.F., Sun, B., 2002. The basic processing of contemporary Chinese corpus at Peking University, Specification. *J. Chin. Inf. Proc.* 16, 49-64.
- Zaidel, E., Kasher, A., Soroker, N., Batori, G., 2002. Effects of right and left hemisphere damage on performance of the “Right Hemisphere Communication Battery”. *Brain Lang.* 80(3), 510–535.
- Zaidel, D.W., Zaidel, E., Oxbury, S.M., Oxbury, J.M., 1995. The interpretation of sentence ambiguity in patients with unilateral focal brain surgery. *Brain Lang.* 51(3), 458–468.
- Zempleni, M., Haverkort, M., Renken, R., Stowe, L.A., 2007. Evidence for bilateral involvement in idiom comprehension: An fMRI study. *Neuroimage* 34, 1280–1291.

Zhang, X., Yu, Y. 2001. A Dictionary of Stories of Chinese Idioms. Inner Mongolia, China: Inner Mongolia Press.

ⁱ We used event-related potentials to investigate the processing of Chinese idioms in a study that addresses a different type of theoretical issue (see Liu et al., 2010).

ⁱⁱ For example, the idiom 叶公好龙 *ye gong hao long*, literally ‘Mr. Ye likes dragons’ comes from a story in the book by Liu Xiang in the Han Dynasty (25-220 AD), which describes a man who claimed to be fond of dragons, with paintings and carvings of dragons all over his house; the real dragon heard this, was deeply moved, and paid Mr. Ye a visit. But when the dragon came to his house, Mr. Ye was scared to death. This four-character idiom has since been used to refer to a situation when someone claims to love something but does not really love it or is in fact afraid of it.

ⁱⁱⁱ Here we used the term *phrase* to refer to both idioms and non-idiomatic phrases.

^{iv} We thank an anonymous reviewer for pointing out the potential influence of imageability. A study by Bedny and Thompson-Schill (2006) also reported stronger activation in left SPL and left fusiform for high imageability words than for low imageability ones.

Table 1 Characteristics and examples of experimental conditions

Condition	Example	Semantic distance	Idiom status	Stroke	Familiarity	Frequency
Opaque idioms	叶公好龙 (ye gong hao long)	4.98 (0.78)	0.98 (0.05)	31.88 (6.48)	6.57 (0.30)	93.81 (87.39)
Transparent idioms	装聋作哑 (zhuang long zuo ya)	2.46 (0.64)	0.90 (0.12)	33.10 (7.11)	6.60 (0.21)	105.23 (62.39)
Non-idiomatic phrases	跳下悬崖 (tiao xia xuan ya)	0.14 (0.25)	0.02 (0.05)	33.27 (6.47)	6.82 (0.18)	107.77 (74.14)

Table 2A Contrast between opaque idioms and baseline condition

brain region	BA	# of voxels	x	y	z	t-value
L PreCG	4	15	-37	-22	50	6.07
L MFG/IFG	9	49	-49	8	35	6.15
	46	64	-40	26	26	7.13
L insula	13/47	52	-34	14	5	7.24
L FFG/PHG	20	64	-25	5	-31	7.42
L FFG/MTG/ITG/IOG/MOG/ PCu/IPL/SPL	37/19/7/39/40	1181	-40	-52	-13	12.74
L LG/Cuneus	18/30	51	-13	-79	5	6.14
L caudate		15	-31	-40	2	-5.8
L thalamus		20	-10	-13	11	5.49
L cerebellum		16	-19	-34	-37	7.2
R IFG/MFG	9/6	86	50	5	29	7.31
R insula	13	77	32	20	14	7.27
R anterior MTG/Uncus	21/38	63	35	2	-31	6.75
R PCu/SPL/ AG	7/19/39	205	29	-67	38	6.89
R MOG/FG/PHG/ITG	18/19/20/37	598	41	-76	-7	8.71
R cuneus	18/23/30	51	17	-67	8	5.48
R thalamus		18	11	-13	11	4.52
B medial frontal gyrus	6/32	260	5	11	44	7.76
B cerebellum		60	2	-55	-28	6.23

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. Voxel size is 3×3×3 mm³. B = Bilateral, L = Left, R = Right, PreCG = Precentral Gyrus, LG = Lingual Gyrus, MFG = Middle Frontal Gyrus, IFG = Inferior Frontal Gyrus, PHG = Parahippocampal Gyrus, MTG = Middle Temporal Gyrus, STG = Superior Temporal Gyrus, PCC = Posterior Cingulate Cortex, SPL = Superior Parietal Lobe, PCu = precuneus, AG = Angular Gyrus, FG = Fusiform Gyrus, MOG = Middle Occipital Gyrus.

Table 2B Contrast between transparent idioms and baseline condition

brain region	BA	# of voxels	x	y	z	t-value
L IFG/MFG	46/45	133	-46	35	8	6.78
L insula	13	39	-28	26	11	6.18
L FFG/ITG/IOG/MOG/ PCu/IPL/SPL	37/19/7/39/40	803	-40	-52	-13	9.93
L FFG	20	28	-40	-4	-22	6.79
L LG/cuneus	18	21	-13	-70	5	5.6
R IFG/MFG	9/46	56	44	11	29	6.17
R insula	47/13	51	29	29	2	7.97
R FFG/IOG/MOG/LG	37/17/18/19	381	35	-82	13	9.06
R SPL/PCu	7/19	130	26	-67	47	7.02
R LG/cuneus	18	25	17	-76	5	6.68
B medial frontal gyrus	6	146	2	5	50	6.73
B cerebellum		15	2	-49	-25	5.58

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. Voxel size is 3×3×3 mm³. B = Bilateral, L = Left, R = Right, LG = Lingual Gyrus, MFG = Middle Frontal Gyrus, IFG = Inferior Frontal Gyrus, MTG = Middle Temporal Gyrus, SPL = Superior Parietal Lobe, PCu = precuneus, FG = Fusiform Gyrus, MOG = Middle Occipital Gyrus.

Table 2C Contrast between non-idiomatic literal phrases and baseline condition

brain region	BA	# of voxels	x	y	z	t-value
L PreCG/IFG/MFG	6/9	74	-34	5	26	5.97
L MFG/IFG	9	22	-43	26	26	5.4
	46	25	-43	38	8	6.05
L insula	13	49	-28	23	5	7.93
L IPL/SPL/PCu	40/39/19/7	229	-46	-46	41	7.3
L FG/PHG/ITG/MOG/IOG	37/18/19	663	-34	-2	-10	10.28
R MFG	9	16	41	20	29	5.45
R insula	45/13	45	32	29	5	6.42
R PHG/FG/IOG/MOG	20/37/18	303	35	-31	-19	8.87
R PCu/AG	7/19	43	26	-64	38	5.38
R cuneus	23	14	14	-73	11	5.16
B CG	32	42	14	17	38	6.58
B SFG/medial frontal gyrus	6	27	2	8	50	5.9

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. Voxel size is 3×3×3 mm³. B = Bilateral, L = Left, R = Right, PreCG = Precentral Gyrus, MFG = Middle Frontal Gyrus, IFG = Inferior Frontal Gyrus, PHG = Parahippocampal Gyrus, FG = Fusiform Gyrus, CG = Cingulate Gyrus, IPL = Inferior Parietal Lobe, SPL = Superior Parietal Lobe, PCu = precuneus, AG = Angular Gyrus, SFG = Superior Frontal Gyrus.

Table 3 Contrast between experimental conditions

brain region	BA	# of voxels	x	y	z	t-value
<i>idioms vs. non-idiomatic phrases</i>						
L LG/FG/MOG	18/19	156	-31	-73	-10	5.8
R SPL/PCu	7	78	14	-73	41	4.81
<i>opaque idioms vs. non-idiomatic phrases</i>						
L LG/FG/MOG	18/19	191	-25	-82	-1	4.65
R SPL/PCu/SMG/PostCG	40/7	160	41	-31	50	4.38
<i>transparent idioms vs. non-idiomatic phrases</i>						
L SMG/PostCG	40/2	71	-40	-28	37	-3.71
<i>opaque idioms vs. transparent idioms</i>						
L SMG	40	72	-40	-31	38	5.22
L Cerebellum		80	-28	-40	-31	4.4
R PostCG/PreCG	3/2/4	228	53	-22	38	4.91
R SPL	7	74	47	-37	56	4.38

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. L = Left, R = Right, LG = Lingual Gyrus, FG = Fusiform Gyrus, MOG = Middle Occipital Gyrus, SPL = Superior Parietal Lobe, PCu = Precuneus, SMG = Supramarginal Gyrus, PostCG = Postcentral Gyrus, PreCG = Precentral Gyrus.

Table 4 Regions of interest (ROIs) defined based on conjunction analysis

brain region	BA	# of voxels	x	y	z
<i>common for both idioms and non-idiomatic phrases</i>					
L MFG/IFG	9	22	-46	11	23
L SPL/PCu	7/19	128	-28	-66	33
R SPL/PCu	7/19	29	29	-64	35
<i>common for idioms only</i>					
R MFG/IFG	9	36	47	14	26
R SPL/PCu	7/19	49	26	-61	41

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. L = Left, R = Right, MFG = Middle Frontal Gyrus, IFG = Inferior Frontal Gyrus, SPL = Superior Parietal Lobe. PCu = Precuneus.

Table 5 Regions modulated by semantic transparency

brain region	BA	# of voxels	<i>x</i>	<i>y</i>	<i>z</i>	t-value
L LG/FG/MOG	18/19	182	-31	-73	-10	4.74
R AG/SPL/PCu	39/7	130	32	-61	35	4.31
L PHG/FG	36/20	73	-37	-34	-13	5.21

Note: Coordinates of peak voxels in Talairach space are reported. BAs are also reported when appropriate. L = Left, R = Right, LG = Lingual Gyrus, FG = Fusiform Gyrus, MOG = Middle Occipital Gyrus, SPL = Superior Parietal Lobe, AG = Angular Gyrus, PCu = Precuneus, PHG = Parahippocampal Gyrus.

Figure captions

Figure 1. Contrasts between the three types of phrases (all corrected to $p < .05$). LH: left hemisphere; RH: right hemisphere.

Figure 2. Brain regions activated for all three types of phrases (Red) and regions showing activations for idioms only (Yellow) during the conjunction analysis. β values in bilateral IFG and bilateral SPL/PCu from the ROI analysis were shown in the bar maps; error bars show ± 1 SE with between-subject variance removed (Loftus & Masson, 1994); *indicates the difference is significant at $p < .05$.

Figure 3. Brain regions in which activation was modulated by semantic distance (corrected to $p < .05$). Left panel – a ventral view of LH; Right panel – a right-back view of RH.

Figure 1
LH

RH

idioms vs. non-idiomatic phrases

opaque idioms vs. non-idiomatic phrases

transparent idioms vs. non-idiomatic phrases

opaque idioms vs. transparent idioms

Figure 2

Figure 3