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The role of motor system in action-related language comprehension in L1 and L2: An fMRI study

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ABSTRACT

The framework of embodied cognition has challenged the modular view of a language-cognition divide by suggesting that meaning-retrieval critically involves the sensory-motor system. Despite extensive research into the neural mechanisms underlying language-motor coupling, it remains unclear how the motor system might be differentially engaged by different levels of linguistic abstraction and language proficiency. To address this issue, we used fMRI to quantify neural activations in brain regions underlying motor and language processing in Chinese-English speakers' processing of literal, metaphorical, and abstract language in their L1 and L2. Results overall revealed a response in motor ROIs gradually attenuating in intensity from literal to abstract via metaphorical language in both L1 and L2. Furthermore, contrast analyses between L1 and L2 showed overall greater activations of motor ROIs in the L2. We conclude that motor involvement in language processing is graded rather than all-or-none and that the motor system has a dual-functional role.

1. Introduction

The way language is represented and decoded in our brain has aroused the interest of researchers from various fields, such as cognitive neuroscience, psychology, linguistics, philosophy, etc. The traditional view of language representation states that language is manifested in our brain as abstract symbols (or forms) in language-specific modules, such as Broca's area and Wernicke's area (see review by Pulvermüller, 2005). From the modular perspective, language is predominantly processed in language domain-specific regions which are independent of the sensory-motor system. This assumption meshes well with the disembodied view of language, which claims that core language processing does not involve the manipulation of sensory-motor information. In addition, the disembodied view of language processing regards language processing as computations of abstract and amodal symbols, which do not interact with information from sensory-motor modalities (see review by Horchak, Giger, Cabral, & Pochwatko, 2014).

The embodied hypothesis, which emerged later, challenged the disembodied view by suggesting that language processing should be considered in the context of the interaction between mind and body (Barsalou, Santos, Simmons, & Wilson, 2008; Gallese, 2005; Gallese & Lakoff, 2015; Fischer & Zwaan, 2008; Pulvermüller & Fadiga, 2010; see review by Wang, Yan, & Guo, 2018; Zwaan, 2014). According to the prevailing embodied view, language symbols are functionally and neuro-anatomically grounded in the sensory-motor system, which is utilized for mental simulation to retrieve meaning (Kiefer & Pulvermuüller, 2012).

Over the past decades, neuroimaging studies have provided accumulating evidence for the involvement of the motor system in language processing (Fargier et al., 2012; Fernandino et al., 2013; Fischer & Zwaan, 2008; Hauk, Johnsrude, & Pulvermüller, 2004; Klepp et al., 2014, 2015; Moreno, de Vega, & León, 2013; Raposo, Mossa, Stamatakis, & Tyler, 2009; Sakreida et al., 2013; Pulvermüller, Shtyrov, & Ilmoniemi, 2005;Tettamanti et al., 2005). These studies have reported that processing words related to body motion engages the motor cortex, especially in the case of literal language (*e.g.* <u>*catch*</u> *the ball*).

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Evidence from clinical studies of patients with motor dysfunction, such as Parkinson's disease (PD), also seems to support the involvement of the motor system in processing action-related literal language. PD patients have been shown to be selectively impaired in the comprehension of action-related words, as suggested by lower behavioral scores as compared with healthy controls (Birba et al., 2017; Boulenger, Hauk, & Pulvermüller, 2009; Buccino et al., 2018; Cardona et al., 2014; Desai, Herter, Riccardi, Rorden, & Fridriksson, 2015; Fernandino et al., 2013; García & Ibáñez, 2014). Interestingly, while healthy controls showed modulation of motor cortex activation specifically by action-related words, PD patients demonstrated a reduction or absence of this modulation in the processing of action-related words (see review by Birba et al., 2017; Buccino et al., 2018). The above studies indicated the engagement of the motor system especially in the processing of concrete words.

Studies from the embodied view have shed light on the importance of the body in language processing, but have received criticism as well. As Chatterjee (2010) has put it, "a quick acceptance of embodied accounts runs the danger of ignoring alternate hypotheses and not scrutinizing neuroscience data critically." Researchers with the "embodied stance" seem to be inclined to interpret the data (especially neuroimaging data) with a prior hypothesis bias, and thus are likely to take the data as additional evidence in support of the embodied view of language processing. This bias of the hypothetical stance of embodiment may cause an oversight of other alternative hypotheses or explanations.

Moreover, oversimplified interpretations fail to advance our understanding of the mechanisms by which motor function could contribute to language processing. Current studies are mainly confined to a dichotomy of all-or-none answer to the question of whether language processing is embodied or not, which does not contribute much to improving our understanding of how the motor system is involved in language processing. Instead, it would be more constructive to give a more-or-less answer to the following question: to what extent is the motor system engaged in different linguistic circumstances? The gradation issue of motor engagement has also been highlighted in Chatterjee (2010) and Meteyard et al.'s reviews (2012) by suggesting that the question of embodied versus disembodied language processing should be replaced by the question of gradations of embodiment.

However, the lopsided explanations of the role of the motor system have also drawn criticism (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012). In neuroimaging studies, motor activations are monolithically interpreted as the involvement of the motor system for mental simulation of word meaning. Meteyard et al. (2012) argued that motor system activations are not necessarily the results of mental simulation of meaning, but might be ubiquitous in general cognitive processes. Therefore, it cannot be justified to take motor activation as evidence to refute the disembodied hypothesis and confirm the embodied hypothesis. Regarding the role of the motor system, it is still unclear that whether motor activation reflects motoric mental simulation of word meaning, or it also reflects other general cognitive functions during language comprehension, such as cognitive control, memory retrieval, prediction and information integration (Francis, 2005; Miller, 2000; Ullman, 2004; Willems, Toni, Hagoort, & Casasanto, 2010).

1.1. *Gradations from the perspective of linguistic abstraction*

The gradation issue mentioned above can be approached by manipulating the degree of linguistic abstraction. Metaphorical language offers valuable information with which we may examine the graded nature of motor system involvement, since it conveys abstract meanings via concrete forms, with its abstractness lying between literal and abstract languages.

Several studies focusing on metaphorical language have recently emerged. However, these studies mainly aim to answer whether or not the motor system is also involved in a more abstract language (metaphorical language), compared with the literal language. Functional MRI studies have been carried out to the investigate BOLD signals of the motor system in metaphorical language processing (Bardolph & Coulson, 2014; Boulenger et al., 2009; Cacciari et al., 2011; Desai, Binder, Conant, & Seidenberg, 2010; Desai, Conant, Binder, Park, & Seidenberg, 2013; Raposo et al., 2009). In Desai et al. (2013), the interaction of language and motor systems was investigated by manipulating the abstractness of action verbs at the sentence level, namely, literal action (*The instructor is grasping the steering wheel very tightly.*), metaphorical action (*The congress is grasping the state of the affairs.*), and idiomatic action (*The congress is grasping at straws in the crisis.*). Results showed activation in motor areas for both literal and metaphoric conditions, but not for idiomatic ones. Similarly, in Boulenger et al. (2009), somatotopic activations (activations corresponding to leg- or arm- effectors) were also found for both literal and metaphorical action sentences embedded with leg- or arm-related verbs (*e.g. grasp; kick*). At the phrase level, motor activation and motor cortex modulation (indexed by motor evoked potentials, MEPs) were investigated by using either fMRI or TMS, indicating that the motor system was involved in both literal (*catch the ball*) and metaphorical (*catch the meaning*) language, but not abstract (*understand the meaning*) language (Cacciari et al., 2011; Desai et al., 2010; Desai et al., 2013). These studies provided supporting evidence for the involvement of the motor system in metaphorical language processing. However, they only analyzed the activation of the motor system without further identifying whether or not the motor activation was due to language processing, which made the interpretation of the data vague.

The role of the motor system in metaphorical language has also been studied by EEG/MEG with cross-modal priming paradigms. In these studies, either motion perception or motion-related language stimuli were used as primers, followed by language comprehension or motor response tasks, respectively (Klepp et al., 2014, 2015; Mollo, Pulvermüller, & Hauk, 2016; Moreno et al., 2015; Santana & de Vega, 2011; Schaller, Weiss, & Müller, 2017; Wilson & Gibbs, 2007). Desynchronization of oscillatory activation at specific frequency bands, namely 8–13 Hz (alpha rhythm, also referred to as mu rhythm) and 15–30 Hz (beta rhythm) has been widely used as an index to indicate the involvement of the motor system. In Schaller et al. (2017), three types of sentences were designed: concrete action sentences (the same as those marked "literal" in the current study) (*e.g.*, *I have pulled the hand break*.), abstract action sentences (the same as those marked "metaphorical" in the current study) (*e.g.*, *I have drawn the consequence*.) and abstract control sentences (*e.g.*, *I have demanded the consequence*.). Concrete and abstract action sentences induced stronger desynchronization in the beta frequency band (16–25 Hz) than abstract control sentences, indicating motor cortex involvement in action-related, but not in abstract language processing.

However, some fMRI and EEG studies reported no signs of motor system involvement in the processing of action-related metaphorical language (Aziz-zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Raposo et al., 2009; Desai et al., 2010; Desai et al., 2013; Bardolph & Coulson, 2014). Aziz-zadeh et al. (2006) found activations of the premotor cortex only for literal action sentences, but not for idiomatic ones (*biting off more than you can chew*). Likewise, Raposo et al. (2009) also found no activation in the premotor and motor regions during comprehension of figurative sentences embedded with action verbs. By adopting an EEG approach and a motor priming paradigm, Bardolph and Coulson (2014) investigated whether vertical arm movements would impact brain activity elicited by literal and metaphorical words with ascending or descending meaning. The congruent effect on EEG activity was found only for the comprehension of literal words, but not for metaphorical words. These studies suggest that motor simulation is merely confined to literal language.

Current studies on metaphorical language comprehension, despite considering the graded nature of motor engagement by manipulating language with different degrees of abstractness, seem only to have given an all-or-none answer to the question about the embodiment of language, without further analyzing the gradations of motor involvement.

1.2. Gradations from the perspective of language proficiency

Another way to explore the graded nature of motor system engagement in language processing is from the perspective of a second language (L2). The degree to which the motor system is engaged is presumably influenced by differences in mental representation, language proficiency and automization between L1 and L2. Characterized by the late AOA (age of acquisition) and insufficient linguistic exposure, L2 is assumed to differ from L1 in terms of its neural representation and decoding system (Abutalebia & Green, 2007; Francis, 2005; Perani & Abutalebi, 2005). In terms of semantic processing, the link between meaning and perception is well established in L1, whereas, in L2, linguistic meaning is mainly accessed through the link between L2 word form and L1 translation equivalent (Vukovic & Shtyrov, 2014). Findings from SLA (second language acquisition) research have provided evidence that L2 learners are used to translating subconsciously (automatically) during the comprehension of L2 due to a heavy reliance on L1 semantic knowledge (Thierry & Wu, 2007; Tokowicz, 2014; Jarvis & Pavlenko, 2008; Degani, Prior, & Tokowicz, 2011). Besides, due to the lack of multi-modal input in L2 acquisition, the mental representation of L2 has been assumed to engage less sensory-motor information and more abstract symbols, compared with L1.

So far, only two studies have investigated the engagement of the motor system in L2 (Vukovic & Shtyrov, 2014; Xue, Marmolejo-Ramos, & Pei, 2015), and only one study has explored the differences of motor involvement between L1 and L2 (Vukovic & Shtyrov, 2014). This study examined whether or not German-English bilinguals would show different degrees of motor system involvement in processing action-related words (literal level) in L1 and L2 by analyzing the event-related desynchronization (ERD) of mu-rhythms (8–12 Hz, 14–20 Hz). Results showed that the ERD of mu-rhythms occurs both in L1 and L2 and is significantly stronger in L1, indicating a higher degree of embodiment in L1. This is the first study that shed light on the gradations of motor system engagement from the perspective of language proficiency.

Exploring the influence of linguistic abstraction and language proficiency on motor system activation can reveal, besides the graded nature, also the functional role of the motor system in language processing. Specifically, it is unclear whether motor activation exclusively reflects motoric mental simulation of word meaning, or whether it also reflects other cognitive functions during general language (non-action related) comprehension such as cognitive control, memory retrieval and information integration (Francis, 2005; Miller, 2000; Ullman, 2004)? This issue can be tentatively scrutinized by utilizing phrases including both action words, which require motoric simulation, and non-action-related abstract words, which do not require motoric simulation.

1.3. The present study

In order to advance our understanding of the role of the motor system in action-related language processing, we address the following questions: (1) to what extent do action-related literal language, action-related metaphorical language, and abstract language engage the motor system and (2) to what extent do L1 and L2 engage the motor system?

In light of the graded abstractness of literal, metaphorical and abstract language, it is presumed that the activation strength of the motor system would follow a hierarchical order, with the greatest motor activation for literal language, the least for abstract language, and a medium level of activation for metaphorical language. In addition, based on the assumption that the mental representation of a language one is less proficient in involves less multi-modal information, we hypothesize that L2 processing might require a lower degree of motor engagement for meaning simulation, compared with L1.

2. Research method

2.1. Participants

A total of 29 (11 male, 18 female) Chinese-English speakers participated in the experiment, with Chinese as their native language (L1) and English as the second language (L2). All participants were right-handed, and had normal or corrected-to-normal vision. No one was reported to have any neurological or psychiatric disorder, nor were they undergoing any pharmacological treatment while doing the experiment. Participants were compensated for their involvement in the experiment. The average age of starting English learning was 11.17 years old and the mean amount of time learning English was 13.14 years. All participants had taken a vocabulary test called Lextale (www.lextale.com) (mean score = 79.00, SD = 5.46). One participant was excluded from data analysis due to uncorrectable head motion. All participants signed informed consent forms approved by the ethics committee of Dalian University of Technology and Affiliated Zhongshan Hospital of Dalian University.

2.2. Experiment design

The present study consisted of two experiments: an L1 Experiment and an L2 Experiment, in which a one-factorial within-subject design was used. The factor *phrase type* was manipulated in the two experiments, including literal, metaphorical and abstract conditions. These three conditions followed a gradual change in abstraction level, designed to explore the degree of motor involvement in understanding meaning with different abstraction levels. Furthermore, a rapid jittered event-related design was adopted in order to model the transient responses of different trial types (Petersen & Dubis, 2012).

2.3. Experiment materials

Materials in the L1 Experiment included 40 triples of L1 (Chinese) visual stimuli (Table 1), including literal, metaphorical, and abstract language. According to Gibbs and Colston (2012), metaphorical language refers to all the expressions, from single words to complete sentences, whose interpretation requires to go beyond the literal meaning of every lexical constituent. In our study, metaphorical language is only confined to verbal metaphors where the literal verbs are used to convey non-literal meanings. The grammatical structure of verbal metaphors is fixed as: verb + noun (*e.g.* catch the meaning). In addition, as indicated by the career of metaphor hypothesis (Bowdle & Gentner, 2005), the abstraction level of a metaphor is affected by its degree of conventionalization. Based on this, the metaphors used in our study are moderately conventionalized metaphors, instead of novel metaphors or dead metaphors.

Action-related (related to hand or arm) verbs were embedded in both literal (抓住皮球, zhuā zhù pí qiú, which means "catch the ball") and metaphorical phrases (抓住意思, zhuā zhù yì sī, which means "catch the meaning"). The same meaning conveyed by the metaphorical phrases was connoted in each abstract phrase (理解意思, lǐ jiě yì sī, which means "understand the meaning") (Table 1). Trials in L1 were virtually semantic-correspondent to those of L2, with some exceptions

Table 1
An example set of experiment materials in the L1 and L2 Experiments.

Types of verb phrase	L1 Experiment	L2 Experiment
Literal	抓住皮球	Catch the ball
Metaphorical	抓住意思	Catch the meaning
Abstract	理解意思	Understand the meaning

due to the non-existence of some English metaphorical expressions in Chinese.

Similarly, materials in the L2 Experiment included 40 triples of English verb phrases within the three aforementioned conditions (Table 1). Action-related words were embedded in both literal and metaphorical phrases in the same way as for the L1 Experiment. Frequency norming tests and familiarity rating tests were conducted to make sure there were no significant differences in the aspects of word length, frequency or familiarity. In order to avoid the L1 priming effect on L2, the L2 Experiment was conducted before the L1 Experiment. Stimuli in both experiments share the same syntactic structure: verb + object.

2.4. Experiment procedure

The L1 Experiment and the L2 Experiment shared the same procedure. Participants were instructed to read phrases of different conditions. The order of trials was pseudo-randomized. Each trial started with a 2000 ms fixation at the center of the screen. Then, a verb phrase appeared with a duration of 2000 ms, followed by a blank interval which varied between 2 and 8 s. Visual stimuli were programmed by the E-prime2.0 and presented by Visual and Audio Stimulation System for fMRI (SAMRTEC SA-9900). After the scanning session, participants were instructed to complete a motor-relatedness scale.

2.5. fMRI acquisition and pre-processing

Participants were scanned in a 3 T Siemens Tim Trio magnetic resonance scanner at Affiliated Zhongshan Hospital of Dalian University. The scanning session consisted of four parts: a resting-state (6′08″), the language experiments (28′28″), a motor localizer task (3′08″) and T1-weighted images (5′43″). In the language experiment session, participants were asked to take a two-minute break after each run (around 5 min). One volume of T2*-weighted, gradient echo, echo-planar images were obtained with the following parameters: FOV: 240×240, resolution matrix:64×64, slice thickness: 4 mm, voxel size: $3.5 \times 3.5 \times 3.5\ mm^3$, flip angle: 90°, TR: 2000 ms, TE: 30 ms. Volumes were composed of 32 axially oriented 4-mm slices with a 1 mm inter-slice gap. Structural T1-weighted 3D images of the whole brain were obtained with $1 \times 1 \times 1\ mm^3$ voxel dimensions at the end of the scanning session.

Pre-processing was done with DPABI (rfmri.org/dpabi). The functional images were slice-time corrected to the middle (16th) slice, realigned to the first image of the run, registered into the MNI152 standard space template, rescaled to a $3 \times 3 \times 3\ mm^3$ resolution, and smoothed with a FWHM 6 mm Gaussian kernel. In the temporal domain, detrend and a band pass filter with 0.01–150 mHz was applied to remove the system interference and abnormal frequency components.

2.6. Behavioral data recording

After the fMRI experiment, participants were asked to recall and rate the degree of motor-relatedness (1: not related at all; 5: closely related) of each verb phrase (including literal, metaphorical, and abstract phrases) first seen in the scanning session.

2.7. Image data processing

The SPM12 (www.fil.ion.ucl.ac.uk/spm/software/spm12/) was used for the individual and group level analysis. The software packages of DPABI (rfmri.org/dpabi) and BrainNet View (www.nitrc.org/projects/bnv/) were used for image inspection and visualization.

2.7.1. Regional effect analysis

According to the experimental paradigm, the onset series of each individual condition (literal, metaphorical and abstract) were calculated. Based on the event-related design, a general linear model (GLM) and hemodynamic response function (HRF) were applied to evaluate the activation of brain regions in SPM12 software. The activation map of each individual condition (literal, metaphorical, abstract) was calculated (GRF correction: voxel value $p < .05$, cluster value $p < .05$, voxel size > 30). Then, contrast analyses between conditions (literal > metaphorical, literal > abstract, metaphorical > abstract) were conducted by setting the contrast matrix in SPM12. Motion correction parameters calculated in pre-processing were included as a regressor in first-level analysis. After contrast analysis between conditions, a second-level group analysis was performed (corrected at a cluster significance threshold $p < 0.05$). Both Brodmann (BA) and AAL templates were used to study group effects and to validate the activation of language and motor ROIs.

Language ROIs were defined based on a combination of the activation map in the silent reading task and earlier meta-analysis pertaining to semantic processing (Binder, Desai, Graves, & Conant, 2009; Rapp, Mutschler, & Erb, 2012). Language ROIs included posterior inferior parietal lobe, middle temporal gyrus, inferior frontal gyrus and angular gyrus. Likewise, motor ROIs were defined based on the activations in the motor localizer task and previous meta-analysis of the neural network of motor imagery (Hétu et al., 2013), and included the precentral cortex, supplementary motor area and premotor cortex.

2.7.2. Functional connectivity analysis

Functional connectivity was estimated using psychophysiological interactions analysis (PPI, (Friston et al., 1997)). PPI is a method used to investigate task-dependent connectivity in the relationship between BOLD activities in different brain areas, which affords an additional opportunity to understand how brain regions interact in a task-dependent manner (O'Reilly, Woolrich, Behrens, Smith, & Johansen-Berg, 2012; McLaren, Ries, Xu, & Johnson, 2012 for review).

The time series of each participant were computed by using the first eigenvariate from all raw voxel time series in each ROI. The BOLD time series were deconvolved using PPI-deconvolution parameter defaults in SPM12 to estimate the neuronal time series for the seed region. PPI regressor was calculated as the element-by-element product of the ROI neuronal time series and a vector coding for the main effect of each condition. This product is re-convolved by the canonical HRF. PPI models were run separately for each participant. The model also included the main effect of the language type convolved by the HRF, and motion parameters as non-interest effects.

Since PPI analysis explores the interaction between the task conditions and the functional connectivity of different ROIs, seed regions need to be selected to search other brain regions with synchronized brain activity in the whole brain. In the present study, the seed region of language ROIs is defined as BA45 (MNI coordinates: BA45: −45, 33, 15; AAL: inferior frontal gyrus) and motor ROIs as BA6 (MNI coordinates: BA6: −39, 3, 30; AAL: precentral gyrus, supplementary motor area), since these brain regions are significantly activated among all participants in the regional effect analysis.

In this study, PPI analysis was performed to estimate the correlation of time series of language and motor ROIs across the three conditions. Contrast analyses between conditions (literal > metaphorical, literal > abstract, metaphorical > abstract) were also performed to examine which condition shows a more significant correlation effect. The generated contrast results were entered into second-level analyses to obtain group-level results. All reported PPI results were corrected at a cluster significance th reshold of $p < 0.05$.

3. Results

3.1. 1. Behavioral results

The evaluation of motor-relatedness of the experimental stimuli was calculated after the scanning session. In the L1 Experiment, the mean scores for motor-relatedness of literal, metaphorical, and abstract phrases were respectively 4.90 (SD = 0.09), 2.28 (SD = 0.27), 1.13 (SD = 0.13), with all three conditions differing significantly from each other ($F_{(2)} = 3255$; $p < .001$). The motor-relatedness of literal phrases was evaluated to be significantly higher than for metaphorical phrases ($p < .001$), which was evaluated significantly higher than for abstract phrases ($p < .001$). In the L2 Experiment, the mean scores of literal, metaphorical, and abstract phrases were respectively 4.49 (SD = 0.24), 1.79 (SD = 0.29), 1.19 (SD = 0.21), with all three conditions differing significantly from each other ($F_{(2)} = 2087$; $p < .001$). Similar to L1, for L2 the motor-relatedness of literal phrases was evaluated to be significantly higher than for metaphorical phrases ($p < .001$), which was in turn evaluated as significantly higher than for abstract phrases ($p < .001$).

3.2. fMRI results

3.2.1. Results of group-level analysis

L1 Experiment (Chinese)

GLM analysis of individual conditions in the L1 Experiment revealed significant activation of motor ROIs BA6 (supplementary motor area) in all three conditions and BA4 (precentral gyrus; supplementary motor area) in the literal condition as shown in Fig. 1a (GRF correction: voxel value < 0.05; cluster value < 0.05; two-tailed). Language ROIs also showed significant activation in each individual condition, including BA21 (middle temporal gyrus), BA39 (angular gyrus; middle temporal gyrus), BA44 (posterior inferior parietal lobe; inferior frontal gyrus) and BA45 (inferior frontal gyrus), as shown in Fig. 1a.

The results of contrast between conditions (literal > metaphorical, literal > abstract, metaphorical > abstract) are shown in Fig. 1b and Table 2 (uncorrected, $p < 0.05$). The results of contrast between each of the two conditions were as follows: (1) literal-metaphorical contrast showed greater BOLD responses for the literal condition in motor ROI BA6 (supplementary motor area) and language ROI BA39 (angular gyrus); (2) literal-abstract contrast showed greater BOLD responses for the literal condition in motor ROI BA6 (supplementary motor area) and language ROIs BA39 (middle temporal gyrus), BA44 (inferior frontal gyrus), BA45 (inferior frontal gyrus) and lower activation in BA21 (middle temporal gyrus); (3) metaphorical-abstract contrast showed greater BOLD responses for the metaphorical condition in motor ROI BA6 (precentral gyrus), language ROIs BA44 (inferior frontal gyrus) and BA45 (inferior frontal gyrus), and lower activation in BA21 (middle temporal gyrus). The hierarchical order of BOLD response strength in motor ROIs in the three conditions can be summarized as: literal > metaphorical > abstract.

Furthermore, the between-contrast results also showed the smallest cluster size and activation strength of motor ROI in literal-metaphorical contrast, compared with literal-abstract and metaphorical-abstract contrast. In addition, the results of literal-abstract contrast are similar to those of metaphorical-abstract contrast.

L2 Experiment (English)

GLM analysis of individual conditions in the L2 Experiment revealed significant activation of motor ROIs BA6 (supplementary motor area) and BA4 (precentral gyrus; supplementary motor area) in all three conditions and language ROIs including BA21 (middle temporal gyrus), BA39 (angular gyrus), BA44 (inferior frontal gyrus) and BA45 (inferior frontal gyrus) (Fig. 2a) (GRF correction: voxel value $p < 0.05$; cluster value $p < 0.05$; two-tailed).

The results of contrasts between the conditions (literal > metaphorical, literal > abstract, metaphorical > abstract) are shown in Fig. 2b and Table 3 (uncorrected, $p < 0.05$). The results of contrasts between each of the two conditions are as follows: (1) literal-metaphorical contrast showed greater BOLD responses for the literal condition in motor ROIs BA4 (supplementary motor area) and BA6 (supplementary motor area), and language ROIs BA21(middle temporal gyrus), BA39 (middle temporal gyrus) and BA45 (inferior frontal gyrus); (2) literal-abstract contrast showed greater BOLD responses for the literal condition in motor ROI BA6 (supplementary motor area), and language ROIs BA39 (middle temporal gyrus), BA44 (inferior frontal gyrus), BA45(inferior frontal gyrus) and lower activation in BA21

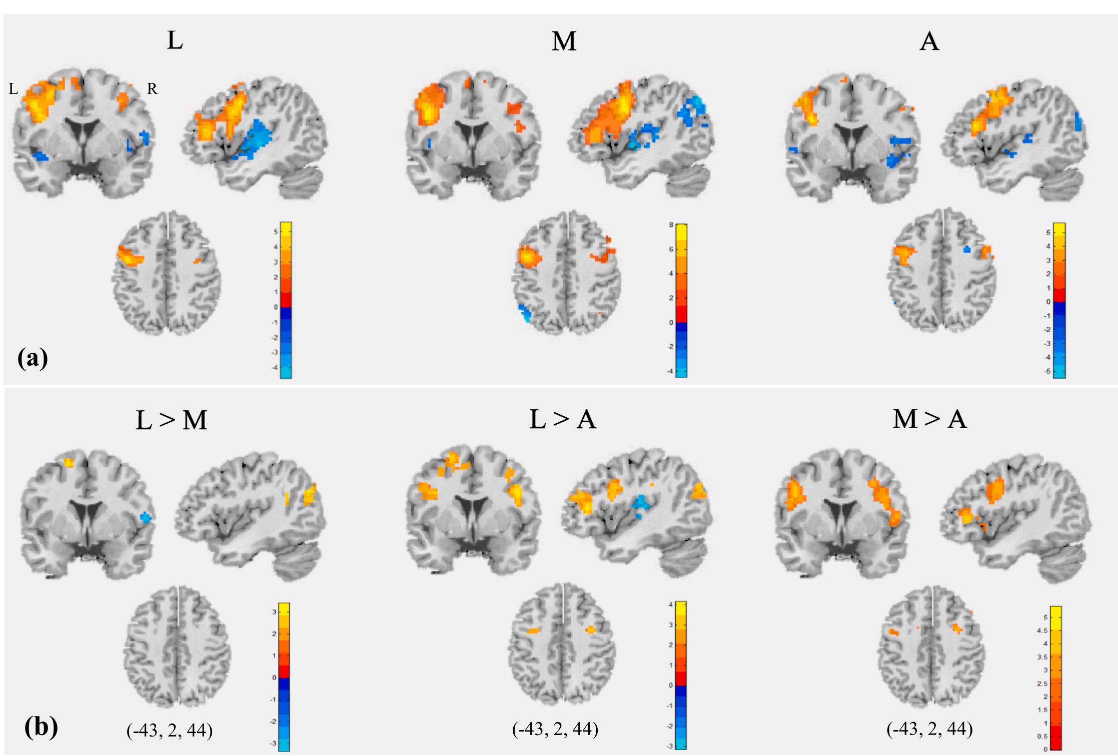

Fig. 1. (a) Activation map of individual conditions in the L1 Experiment. (L: Literal; M: Metaphorical; A: Abstract. GRF correction: voxel value $p < 0.05$, cluster value $p < 0.05$, voxel size > 30). **(b)** Activation map of contrasts between conditions in the L1 Experiment (uncorrected, $p < 0.05$, voxel size > 30).

Table 2
MNI coordinates of peak activations of language and motor ROIs in the L1 Experiment ($p < 0.05$, voxel size > 30).

	T value	x	y	z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
L > M	3.345	−21	−3	54	L	Supplementary motor area	BA6	49
	2.992	−48	−72	33	L	Angular gyrus	BA39	83
L > A	4.169	−18	6	66	L	Supplementary motor area	BA6	300
	−4.799	−48	0	−24	L	Middle temporal gyrus	BA21	55
	3.142	39	−51	21	R	Middle temporal gyrus	BA39	167
	3.459	−42	9	27	L	Inferior frontal gyrus	BA44	192
	4.150	−48	36	12	L	Inferior frontal gyrus	BA45	165
M > A	3.789	−51	6	24	L	Precentral gyrus	BA6	210
	−2.873	−51	0	−24	L	Middle temporal gyrus	BA21	101
	5.428	45	9	21	R	Inferior frontal gyrus	BA44	226
	4.264	−42	33	3	L	Inferior frontal gyrus	BA45	194

(Note: L = Literal; M = Metaphorical; A = Abstract; Hem = Hemisphere; L = left; R = Right; Anatomical regions defined by the AAL template do not have one-to-one correspondence with regions defined by the Brodmann template. One Brodmann region may include several brain regions defined by the AAL template.)

(middle temporal gyrus); (3) metaphorical-abstract contrast showed greater BOLD responses for the metaphorical condition in motor ROI BA6 (supplementary motor area), and lower activation in language ROIs including BA21 (middle temporal gyrus), BA39 (angular gyrus), BA44 (angular gyrus) and BA45 (inferior frontal gyrus). Therefore, a hierarchical order of BOLD response strength of motor ROIs in the three conditions can be summarized as: literal > metaphorical > abstract.

Between-contrast results showed the smallest cluster size and the lowest activation strength of motor ROIs in metaphorical-abstract contrast, compared with literal-metaphorical and literal-abstract contrast. In addition, the results of literal-metaphorical contrast are similar to those of literal-abstract contrast.

Contrast between languages

The contrast between L1 and L2 in the three conditions revealed overall greater activation in L2 across the three conditions (Fig. 3 and Table 4). For the literal condition, greater activation was revealed in BA4 (precentral gyrus), BA6 (precentral gyrus) and BA39 (middle temporal gyrus); for the metaphorical condition, greater activation was found in BA6 (precentral gyrus) and BA21 (middle temporal gyrus); for the abstract condition, greater activation was revealed in BA6 (precentral gyrus), BA21(middle temporal gyrus), BA39 (middle temporal gyrus), BA44 (inferior frontal gyrus) and BA45(inferior frontal gyrus).

3.2.2. *Results of PPI analysis*

L1 Experiment (Chinese)

In the PPI analysis, we analyzed functional connectivity between language and motor ROIs using BA45 as the seed region for language areas and BA6 as the seed region for motor areas. The results (Fig. 4 and Table 5) showed that for the literal-metaphorical contrast (uncorrected, $p < 0.05$), the connectivity between seed region BA45 (inferior frontal

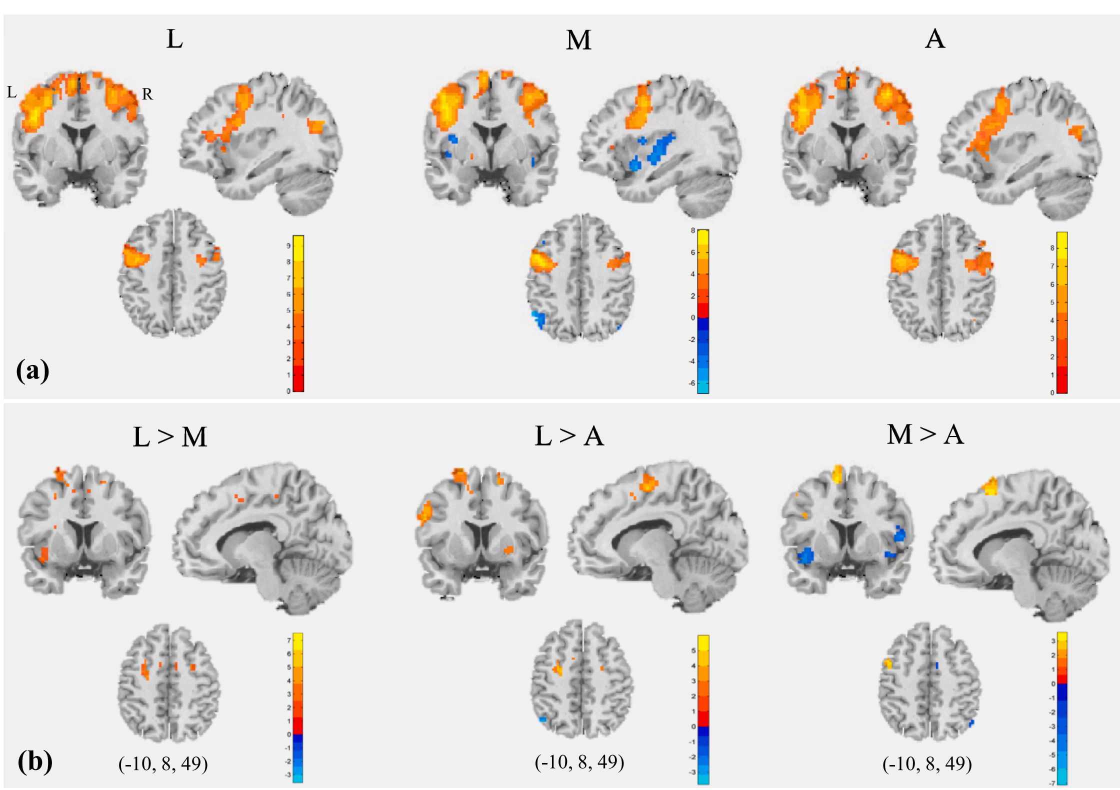

Fig. 2. **(a)** Activation map of individual conditions in the L2 Experiment (GRF correction: voxel value $p < 0.05$, cluster value $p < 0.05$, voxel size > 30). **(b)** Activation map of contrasts between conditions in the L2 Experiment (uncorrected, $p < 0.05$, voxel size > 30).

Table 3
MNI coordinates of peak activations of language and motor ROIs in the L2 Experiment ($p < 0.05$, voxel size > 30).

	T value	x	y	z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
L > M	4.599	12	−27	54	R	Supplementary motor area	BA4	38
	2.964	−18	0	63	L	Supplementary motor area	BA6	284
	4.700	51	−48	3	R	Middle temporal gyrus	BA21	159
	5.272	−45	−72	21	L	Middle temporal gyrus	BA39	478
	3.590	45	36	6	R	Inferior frontal gyrus	BA45	202
L > A	4.405	−9	−6	57	L	Supplementary motor area	BA6	443
	−2.975	−51	6	−27	L	Middle temporal gyrus	BA21	70
	3.224	−42	−51	15	L	Middle temporal gyrus	BA39	186
	4.272	−54	12	30	L	Inferior frontal gyrus	BA44	65
	3.595	−42	42	15	L	Inferior frontal gyrus	BA45	151
M > A	3.619	−9	12	63	L	Supplementary motor area	BA6	108
	−3.156	−60	−18	−15	L	Middle temporal gyrus	BA21	97
	−4.338	−48	−72	33	L	Angular gyrus	BA39	560
	−4.338	−48	−72	33	L	Angular gyrus	BA44	32
	−2.152	−51	18	0	L	Inferior frontal gyrus	BA45	109

(Note: L = Literal; M = Metaphorical; A = Abstract; Hem = Hemisphere; L = left; R = Right)

gyrus) and BA4 (precentral gyrus)/BA6 (supplementary motor gyrus) was greater in the metaphorical condition than in the literal condition. For the literal-abstract contrast (uncorrected, $p < 0.05$), the connectivity between seed region BA45 (inferior frontal gyrus) and BA4 (precentral gyrus)/BA6 (supplementary motor gyrus) was greater in the abstract condition than in the literal condition. For the metaphorical-abstract contrast (uncorrected, $p < 0.05$), the connectivity between seed region BA45 (inferior frontal gyrus) and BA4 (supplementary motor gyrus)/BA6 (precentral gyrus) was greater in the abstract condition than in the metaphorical condition. PPI analysis was also performed with motor ROI BA6 as the seed region. Similar results were obtained (Table 5). In summary, the strength of functional connectivity between language and motor ROIs for the three conditions follows a hierarchical decreasing order (literal < metaphorical < abstract).

The results revealed a dissociation of the BOLD response strength in motor ROIs and functional connectivity of motor-language ROIs. The BOLD responses revealed by GLM analysis showed a hierarchically increasing order of the three conditions (literal > metaphorical > abstract), whereas PPI analysis showed a gradually decreasing order of functional connectivity strength (abstract > metaphorical > literal).

L2 Experiment (English)

In the L2 Experiment, PPI analysis results (Fig. 5 and Table 6) showed that for the literal-metaphorical contrast (uncorrected, $p < 0.05$), connectivity between seed region BA45 (inferior frontal gyrus) and BA4 (precentral gyrus)/BA6 (supplementary motor gyrus) was greater in the literal condition than in the metaphorical condition. For the literal-abstract contrast (uncorrected, $p < 0.05$), the connectivity between seed region BA45 (inferior frontal gyrus) and BA6 (supplementary motor gyrus) was greater in the literal condition than in the abstract condition. For the metaphorical-abstract contrast (uncorrected, $p < 0.05$), the connectivity between seed region BA45 (inferior frontal gyrus) and BA4 (supplementary motor gyrus)/BA6 (supplementary motor gyrus) was greater in the metaphorical condition than in the abstract condition. PPI analyses showed similar results with motor ROI BA6 as the seed region. In summary, PPI analysis of the L2 Experiment showed a hierarchically increasing strength of functional connectivity across the three conditions (literal > metaphorical > abstract).

4. Discussion

The present study investigated brain activations and functional connectivity of language-motor systems in the comprehension of action-related language with different abstraction levels (literal, metaphorical and abstract) in both L1 (native language) and L2 (second language). Results overall revealed a response in motor ROIs (BA4: precentral gyrus; BA6: supplementary motor area) gradually decreasing in intensity from literal to abstract via metaphorical language in both L1 and L2. Furthermore, contrast analyses between L1 and L2 showed overall greater activations of motor ROIs in the L2. PPI analysis

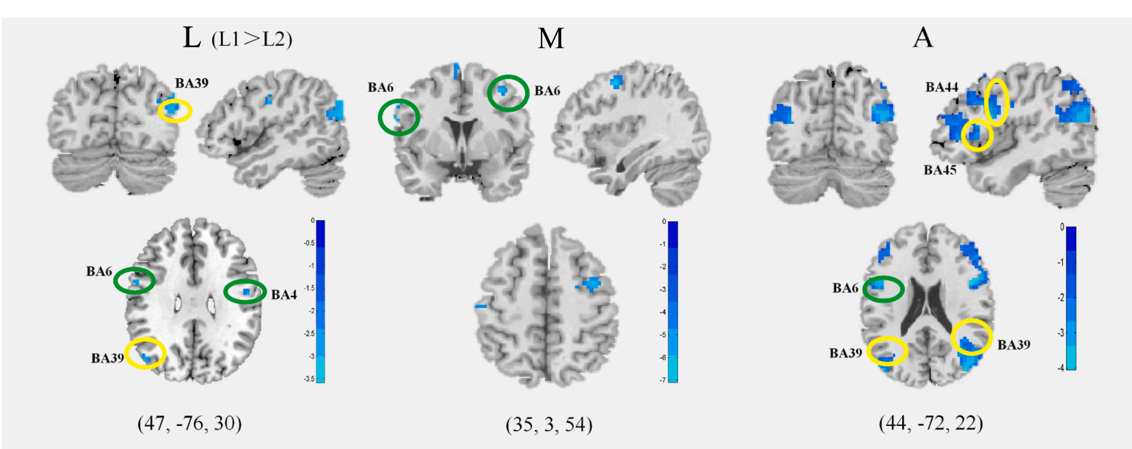

Fig. 3. Activation map of contrasts between L1 and L2 Experiments. (Green circles represent motor ROIs and yellow circles represent language ROIs; uncorrected, $p < 0.05$, voxel size > 30).

Table 4
MNI coordinates of peak activations of contrast between L1 and L2 Experiments ($p < 0.05$, voxel size > 30).

	T value	x	y	z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
L	−2.268	−51	−6	30	L	Precentral gyrus	BA4	32
	−3.393	−39	−6	57	L	Precentral gyrus	BA6	59
	−2.980	48	−75	24	R	Middle temporal gyrus	BA39	81
M	−4.046	−60	9	33	L	Precentral gyrus	BA6	112
	−2.216	−48	−42	9	L	Middle temporal gyrus	BA21	54
A	−6.824	−48	3	27	L	Precentral gyrus	BA6	772
	−4.417	54	−48	−6	R	Middle temporal gyrus	BA21	236
	−5.847	45	−72	21	R	Middle temporal gyrus	BA39	456
	−6.993	−48	6	27	L	Inferior frontal gyrus	BA44	395
	−4.687	42	33	3	R	Inferior frontal gyrus	BA45	371

Note: L = Literal; M = Metaphorical; A = Abstract; Hem = Hemisphere; L = left; R = Right.

validated the correlation between language and motor activations in all conditions in the L1 and L2 Experiments.

4.1. Gradations of motor engagement varying with linguistic abstraction

Our findings corroborated previous studies showing the involvement of the motor system in the processing of action-related language at the literal level in L1 (Fargier et al., 2012; Fernandino et al., 2013; Fischer & Zwaan, 2008; Hauk et al., 2004; Klepp et al., 2014, 2015; Moreno et al., 2013; Raposo et al., 2009; Sakreida et al., 2013; Pulvermüller et al., 2005;Tettamanti et al., 2005) and at the metaphorical level in L1 (Boulenger et al., 2009; Cacciari et al., 2011; Desai et al., 2010; Desai et al., 2013; Santana & de Vega, 2011; Schaller et al., 2017) and at the literal level in L2 (Vukovic & Shtyrov, 2014).

More importantly, the results showed an attenuated motor activation from literal to metaphorical to abstract language, in both L1 and L2. The decremental tendency of motor activation has also been reported by Desai et al. (2013). According to Desai et al., the reliance on the sensory-motor system decreases with the increase in abstractness of meaning. In terms of the abstractness, metaphorical language, with concrete form but abstract meaning, lies between literal and abstract language. However, despite the similar hierarchical pattern of motor activation in L1 (Chinese) and L2 (English) in the present study, the degree of motor activation at the metaphorical level differs between the two languages.

In the L1 Experiment, the difference in motor activation between the literal versus metaphorical conditions is smaller than the difference between the metaphorical versus abstract conditions or between the literal versus abstract conditions, which suggests a similar degree of motor involvement in literal and metaphorical language. Metaphorical language, regardless of the abstract meaning it conveys, seems thus to engage the brain mechanism that is close to concrete, literal language. This interpretation is supported by Schaller et al. (2017) who also showed, by using EEG, that abstract action language (the same concept as action-related metaphorical language in the present study) is processed more similarly to concrete action language than abstract control sentences in L1. The similar degree of motor involvement in metaphorical and literal language might be attributed to the mental simulation of action meaning, since they share the same action word in the verb phrases. The similar degree of motor activation between metaphorical and literal language supports the view that the metaphorical use of a verb preserves the literal meaning (referred to as "basic semantic component" in Cacciari et al.'s study) of the verb (Cacciari et al., 2011).

In addition to sharing the same word form, the way we have learned metaphorical language might also account for the similar involvement of the motor system in literal and metaphorical language in L1. By the time metaphorical usage is acquired, literal usage is already well mastered and supported by rich multi-modal (sensory-motor) associations. Therefore, the conceptual representation of metaphorical language, the meaning of which is evolved from its literal use, might be influenced by the same perceptual and sensory-motor information associated with literal language representation. Specifically for Chinese, the logographic nature of Chinese characters may also contribute to the similar motor activation in metaphorical and literal language. In the Chinese language, virtually all the action verbs associated with hand or arm movement share the same radical 扌 in the written form to indicate that the meaning of the character is associated with hand or arm movement (*e.g.* 抓/grasp, 扔/throw, 擦/wipe, 撕/tear, 推/push). Since the same action character is embedded in the literal and metaphorical stimuli, it would be more likely to evoke similar motor responses as a result of the same semantic clue, especially in the context of written language.

Similar to the L1, the graded engagement of the motor system is also revealed for the L2 (literal > metaphorical > abstract). However, for the L2, the involvement of the motor system in metaphorical language is more similar to its corresponding abstract language, as suggested by the similar motor activation pattern between the metaphorical and abstract conditions. The similar motor involvement of metaphorical and abstract language suggests that the processing of metaphorical language in the L2 shares similar underlying mechanisms with that of abstract language. Since metaphorical language usually conveys

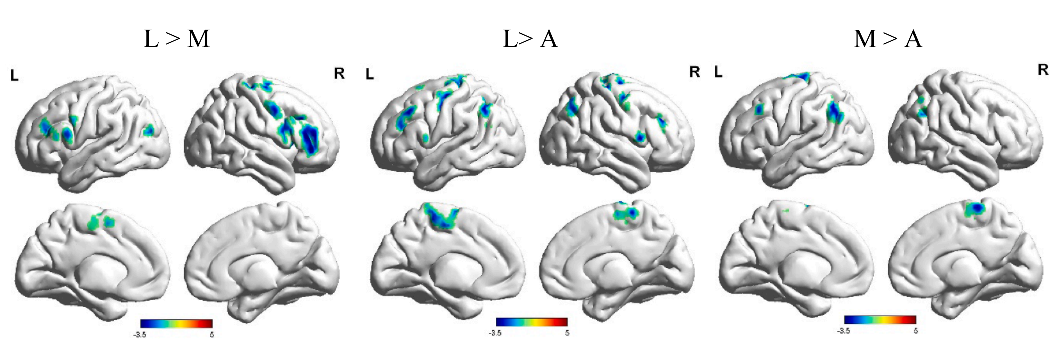

Fig. 4. PPI results of between-condition contrasts in the L1 Experiment (uncorrected, $p < 0.05$; voxel size > 20).

Table 5
MNI coordinates of peak activations obtained in PPI analyses in the L1 Experiment ($p < 0.05$, voxel size > 20).

	Seed Region	T value	x	y	z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
L > M	BA45	−3.120	39	−24	63	R	Precentral gyrus	BA4	52
		−3.881	−9	−12	57	L	Supplementary motor area	BA6	228
	BA6	−3.053	54	−30	−3	R	Middle temporal gyrus	BA21	69
L > A	BA45	−4.969	12	−24	66	R	Precentral gyrus	BA4	302
		−4.049	−9	−12	57	L	Supplementary motor area	BA6	529
	BA6	−3.494	66	−36	−6	R	Middle temporal gyrus	BA21	70
		−3.103	39	9	36	R	Inferior frontal gyrus	BA44	155
		−3.802	48	39	3	R	Inferior frontal gyrus	BA45	129
M > A	BA45	−3.880	12	−21	66	R	Supplementary motor area	BA4	99
		−3.503	−27	−27	60	L	Precentral gyrus	BA6	140
	BA6	*	*	*	*	*	*	*	*

Note: L = Literal; M = Metaphorical; A = Abstract; Hem = Hemisphere; L = left; R = Right; * indicates no significant cluster exists.

abstract meaning, metaphorical phrases and expressions are usually translated into a chunk of abstract words during the learning phase, with their literal meaning being covered by the abstract translation. Consequently, instead of the literal meaning that L2 metaphorical language conveys, L2 learners tend to associate it with the abstract L1 translation equivalent automatically. Therefore, the processing manner of metaphorical language in L2 is more prone to abstract language rather than literal language, which does not utilize motoric simulation to the same degree as L1, but relies more on abstract lexical-semantic decoding (Desai et al., 2010).

4.2. Gradations of motor engagement varying with language proficiency

Since previous studies were mainly concerned with the role of the motor system in L1, the degree to which motor system engagement in L2 is relative to L1 has rarely been discussed. Only in Vukovic and Shtyrov (2014) study, was it concluded that the neural representation of L1 is more embodied than L2, as suggested by greater mu-rhythm ERD (less mu-rhythm power) elicited by L1 words than L2 words. It is interpreted that the higher degree of embodiment in L1 is due to the highly integrated action–perception circuits in L1 which are established by rich linguistic experience.

Concerning how the mu-rhythm ERD in EEG studies relate to the BOLD signals in fMRI studies, studies (Laufs et al., 2003; Ritter, Moosmann, & Villringer, 2008) using simultaneous EEG-fMRI techniques have indicated that the power of mu rhythms is inversely related to strength of BOLD signals in motor cortex. Accordingly, greater ERD of mu rhythm should be correspondent to greater BOLD signals. However, inconsistent with Vukovic and Shtyrov's finding of greater ERD of mu-rhythm in the L1 than the L2, the present study revealed overall greater BOLD signals in motor ROIs in the L2 rather than the L1.

The current results, being inconsistent with those of previous studies, beg the question: does greater motor activation in L2 in the present study imply a higher degree of embodiment? This possibility can be ruled out by the fact that abstract language (as a baseline condition), which does not involve any action-related meaning nor is likely to engage motoric simulation, also induces a higher degree of motor activation in L2 (relative to L1). Thus, the greater motor activation in L2 is not likely to reflect mental action simulation and therefore might not necessarily imply a higher degree of embodiment. There are a few notions that support this interpretation. First, the greater motor activation in L2 compared with L1 is not exclusively linked to action-related language, but also to abstract language which is non-action-related. This generally greater activation, especially for abstract language in L2, indicates that motor system involvement is not exclusively linked with action-related semantic simulation, but language processing in general. Second, in the motor-relatedness evaluation, participants tended to rate the action-related stimuli in L2 (English) less motor-related than in L1 (Chinese). This directly supports the above assumption that greater motor activation in the present study does not imply a higher degree of embodied simulation. Third, the assumption that action-related language is processed in a less embodied way in L2 and more embodied in L1 can be supported by the way that L1 and L2 are acquired. It has been generally acknowledged that native language is usually acquired with multi-modal inputs of sufficient quality and quantity, which contributes to the robust linkage in sensory-motor information in L1 semantic representation. In contrast, L2 words are usually learned in the absence of contextualized input by memorizing their equivalent translation of L1 words (Degani et al., 2011; Jiang, 2000; Kroll, van Hell, Tokowicz, & Green, 2010; Thierry & Wu, 2007). Thus, L2 words are assumed to be represented in a more symbolic form and less associated with the perceptual information they are linked to (Xue et al., 2015). As a consequence of the differences in mental representation, the processing of action-related language in L2, both at the literal and metaphorical levels, is not likely to involve the same degree of motoric simulation as in L1.

What, then, could be the reason for the overall greater motor response in L2 than in L1? We propose that the overall greater motor response in L2 reflects increased demands for cognitive control, such as memory retrieval, execution control, information integration, etc.

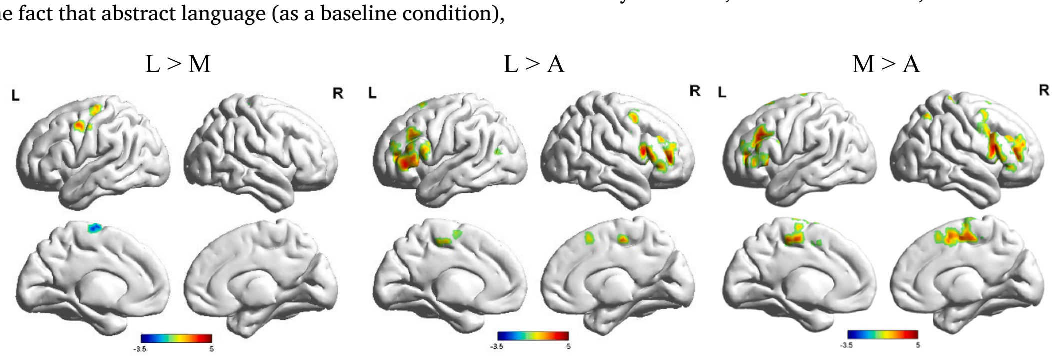

Fig. 5. PPI results of between-condition contrasts in the L2 Experiment (uncorrected, $p < 0.05$, voxel size > 20).

Table 6
MNI coordinates of peak activations obtained in PPI analyses in the L2 Experiment ($p < 0.05$, voxel size > 20).

	Seed Region	T value	x	y	z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
L > M	BA45	2.633	−39	−21	69	L	Precentral gyrus	BA4	61
		−2.414	−9	−9	72	L	Supplementary motor area	BA6	77
	BA6	*	*	*	*	*	*	*	*
L > A	BA45	4.331	15	12	54	R	Supplementary motor area	BA6	376
	BA6	3.724	−51	36	21	L	Inferior frontal gyrus	BA45	135
M > A	BA45	3.286	−3	−21	54	L	Supplementary motor area	BA4	67
		3.785	−6	3	78	L	Supplementary motor area	BA6	413
	BA6	3.514	−54	36	3	L	Inferior frontal gyrus	BA45	83

Note: L = Literal; M = Metaphorical; A = Abstract; Hem = Hemisphere; L = left; R = Right; * indicates no significant cluster exists.

(Francis, 2005; Miller, 2000; Ullman, 2004) in processing a less automatized language. It has been assumed that L2, as a less automatic language (compared with the highly-automatic L1), requires more cognitive resources (Perani & Abutalebi, 2005), which would consequently induce greater motor activation. Indeed, the motor system has been shown to be involved in cognitive control, memory retrieval, prediction and information integration (Francis, 2005; Miller, 2000; Ullman, 2004; Willems et al., 2010). Another potential reason might be that the L2 is not yet fully mastered, and participants actually "sound out" the words to help retrieve the meaning, which would also contribute to greater motor activations.

4.3. The dual-functional role of the motor system in language processing

Current results of the overall greater motor activation in L2 (relative to L1) and motor activation not only in action-related language but also in abstract language invites the consideration of a dual-functional role of the motor system in language comprehension. So far, the functional role of the motor system has been monolithically discussed within the linguistic scope (motoric simulation of meaning) (Bardolph & Coulson, 2014; Cacciari et al., 2011; Fargier et al., 2012; Fernandino et al., 2013; Fischer & Zwaan, 2008; Hauk et al., 2004; Klepp et al., 2014, 2015; Moreno et al., 2013; Raposo et al., 2009; Sakreida et al., 2013; Pulvermüller et al., 2005; Schaller et al., 2017; Tettamanti et al., 2005), and has rarely been considered to reflect functions other than language-related functions, which would include *e.g.* cognitive control and inhibition, information integration, (procedural) memory retrieval (Francis, 2005; Miller, 2000; Ullman, 2004; Willems et al., 2010). The latter may not seem directly linked to language processing, but actually plays an indispensable role in supporting successful language comprehension (as shown in Fig. 6). Indeed, semantic processing and cognitive control are closely intertwined during language comprehension, and may have developed (both phylogenetically and ontogenetically) in an integrated manner. Moreover, these functions have been shown to engage areas included in our motor ROIs including the prefrontal cortex and supplementary motor cortex (see review by Miller, 2000; Ullman, 2004).

In our study, both action-related words and non-action-related abstract words were found to evoke motor responses, which indicates that the motor system might play a more general role in language processing as well as the mental simulation of word meaning. Previous studies have also reported motor involvement in language processing, regardless of the linguistic features (action-related or not) (Dreyer & Pulvermüller, 2018; Guan, Meng, Yao, & Glenberg, 2013; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017). In Vukovic et al. (2017), it was shown that rTMS in motor areas not only affects behavioral responses to action-related language, but also facilitates abstract word responses, which implies that the motor system is not only for mental simulation but also modulates other types of language processing.

Direct evidence of the motor system playing a more general role in language processing comes from studies of patients with motor impairment such as Parkinson's disease (PD), Huntington's disease and cerebral palsy (Birba et al., 2017; Buccino et al., 2018; Cardona et al., 2014). PD patients are reported to be more selectively impaired for action-related verbs (relative to abstract verbs), which is attributed to the inability to perform motoric mental simulation (this is known as the semantic simulation function of the motor system). However, it has long been ignored that the overall language performance of PD patients is also more effort-demanding compared with healthy control participants (Birba et al., 2017; Buccino et al., 2018; Cardona et al., 2014; Fernandino et al., 2013). In these studies, the PD group exhibited longer reaction time and lower accuracy for both action-related words and non-action-related ones than the control group. These results indicate

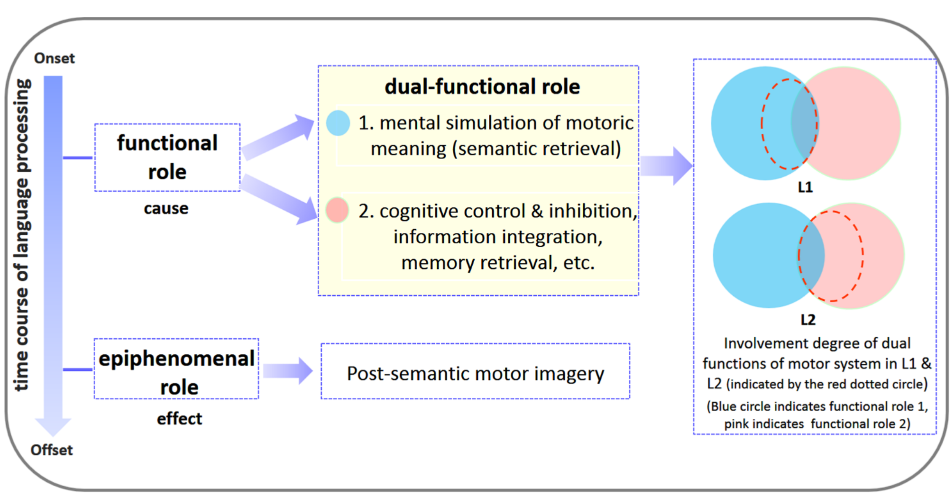

Fig. 6. Schematic view of the dual-functional role of the motor system in the L1 and L2 processing.

that motor dysfunctions not only influence action-related language but language processing overall. However, this overall lower performance has rarely been focused on in discussions, due to the main focus being directed to mental simulation functions of the motor system proposed by embodied cognition. Dating back to research two decades ago, motor circuits have been reported to contribute to semantic understanding and syntactic parsing (see review by Pulvermüller & Fadiga, 2010). Thus, in addition to mental simulation (the mirror neuron system), the motor system may also play an important role in cognitive control and inhibition, as well as memory retrieval and information integration in language processing. This assumption is in line with our findings that L2 evokes overall greater motor activation than L1, since for a less proficient language, more motor resources are needed to manage cognitive control, memory retrieval and information integration. In short, the role of the motor system in language comprehension may be more diverse than previously assumed in the theories of pure motor simulation.

5. Conclusion

With the aim of exploring the graded nature of motor system engagement in language processing, our study shows that motor engagement varies with the degree of linguistic abstraction and language proficiency. In addition, this study proposes the notion of a dual-functional role of the motor system in language processing, which invites further discussion for alternative interpretations of the role of the motor system in language processing.

Statement of significance

This study explored the graded nature of motor system involvement in language processing, which has not been scrutinized in previous studies. The findings that the degree of motor involvement varies with linguistic abstraction and language proficiency bring novel insights to the role of motor system in different linguistic circumstances.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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