## **JYU DISSERTATIONS 644**

# Lili Tian

# Orchestration of Language and Motor Systems in Language Understanding

**Neuroimaging Investigations** 





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# **Neuroimaging Investigations**

Esitetään Jyväskylän yliopiston kasvatustieteiden ja psykologian tiedekunnan suostumuksella julkisesti tarkastettavaksi yliopiston vanhassa juhlasalissa S212 toukokuun 31. päivänä 2023 kello 12.

Academic dissertation to be publicly discussed, by permission of the Faculty of Education and Psychology of the University of Jyväskylä, in building Seminarium, old festival hall S212, on May 31, 2023, at 12 o'clock.



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## ABSTRACT

Tian, Lili

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Over the past few decades, neuroimaging studies have provided evidence for the involvement of the motor system in semantic processing. However, the way that the motor system contributes to semantic processing is still understudied. In this dissertation, neuroimaging techniques (fMRI and MEG) were applied to explore the interaction between language and motor systems in reading verb phrases with varying abstractness in native (L1) and second language (L2). By using fMRI, **Study I** investigated the effect of abstractness (literal/metaphorical/abstract) and language proficiency (L1/L2) on the involvement of the motor system. Results showed attenuated motor activation from literal to abstract via metaphorical phrases in both L1 and L2. In addition, overall greater motor activation was found for L2 than L1. The graded motor involvement modulated by abstractness and the greater motor activation in L2 suggested a dualfunctional role of the motor system in semantic processing. By employing MEG, Study II further investigated temporal dynamics of the involvement of language and motor regions in L1 and L2 processing. Results showed greater activation of language areas for L1 than L2 during 300-500 ms and greater activation of motor areas for L2 than L1 at 600-800 ms. No effect of abstractness was found. The underactivation in language areas in the early stage and overactivation in motor areas in the late stage suggested a compensatory role of the motor system in L2 semantic processing, i.e., over-recruitment of the motor system to compensate for the inadequate engagement of the language network. Study III investigated spatiotemporal dynamics of abstract concept processing in L1. Results showed delayed activation in the posterior superior temporal sulcus at 200-300 ms for abstract phrases relative to concrete and metaphorical ones. In addition, greater activation in the anterior temporal pole at 300-400 ms was found for abstract phrases. Findings shed light on the spatiotemporal dynamics of abstract concept processing. In summary, by exploring the time-varying interplay between the motor and language systems, the above studies deepen our understanding of how the motor cortex contributes to language understanding and bring alternative interpretations of the functional role of the motor cortex in language processing.

*Keywords:* language processing, motor system, fMRI, MEG, language proficiency, abstractness

## TIIVISTELMÄ (ABSTRACT IN FINNISH)

Tian, Lili Kielellisen ja motorisen järjestelmän orkestrointi kielen ymmärtämisessä: neurokuvantamisen tutkimukset Jyväskylä: Jyväskylän yliopisto, 2023, 57 s. (JYU Dissertations ISSN 2489-9003; 644) ISBN 978-951-39-9583-6 (PDF)

Muutaman viime vuosikymmenen aikana aivokuvantamistutkimukset ovat antaneet näyttöä siitä, että motorinen järjestelmä osallistuu kielen merkityksen käsittelyyn, mutta sen tarkempaa roolia semanttisessa prosessoinnissa ei kuitenkaan tunneta. Tässä väitöskirjassa käytettiin aivokuvantamismenetelmiä (funktionaalinen magneettikuvaus, fMRI ja magnetoenkefalografia, MEG) selvittämään, millä tavoin aivojen kielelliset ja motoriset järjestelmät osallistuvat kielen merkityksen käsittelyn. Tätä tutkittiin käyttämällä kirjoitettuja lauseita, joiden abstraktiotaso vaihteli konkreettisesta metaforiseen ja edelleen abstraktiin merkitykseen. Lisäksi selvitettiin eroja äidinkielen (L1) ja toisen vieraan kielen (L2) käsittelyssä. Tutkimuksessa I selvitettiin fMRI:n avulla abstraktiuden (kirjaimellinen/metaforinen/abstrakti) ja kielitaidon (L1/L2) vaikutusta motorisen järjestelmän osallistumiseen lauseiden ymmärtämiseen. Tulokset osoittivat, että motorisen järjestelmän aktivaatio heikkenee, kun siirrytään konkreettisesta kielestä metaforiseen ja edelleen abstrakiin kieleen. Lisäksi motorinen aktivaatio oli yleisesti ottaen suurempi L2:ssa kuin L1:ssä. Kielen abstraktiuden tason vaikutus motorisen järjestelmän aktivoitumiseen sekä suurempi motorinen aktivaatio L2 kielessä viittaavat siihen, että motorisella järjestelmällä on kaksitahoinen rooli semanttisessa prosessoinnissa. Tutkimuksessa II selvitettiin MEG:n avulla kielellisten ja motoristen alueiden ajallista dynamiikkaa L1- ja L2- kielen käsittelyssä. Tulokset osoittivat, että kielellisten alueiden aktivoituminen oli voimakkaampaa L1:n kuin L2:n käsittelyn aikana 300-500 ms lauseen esittämisestä ja motoristen alueiden aktivoituminen oli voimakkaampaa L2:n kuin L1:n käsittelyn aikana 600-800 ms lauseen esittämisestä. Abstraktisuuden vaikutusta ei havaittu. Kielialueiden vähäisempi aktivoituminen alkuvaiheessa ja motoristen alueiden voimakkaampi aktivoituminen myöhäisvaiheessa viittaa siihen, että motorisella järjestelmällä on kompensoiva rooli L2 -kielen merkityksen käsittelyssä. Toisin sanoen, motorinen järjestelmä näyttäisi tukevan kielen ymmärrystä tilanteessa, jossa kielellisten alueiden toiminta on riittämätöntä. Tutkimuksessa III tarkasteltiin abstraktien käsitteiden käsittelyn ajallista ja spatiaalista dynamiikkaa L1 -kielessä. Tulokset osoittivat, että suhteessa konkreettisiin ja metaforisiin lauseisiin abstraktien lauseiden herättämä aktivaatio ylemmän ohimopoimun uurteen takaosissa on viivästynyt 200-300 ms aikaikkunassa lauseiden esittämisestä. Lisäksi abstraktien lauseiden kohdalla havaittiin muita lausetyyppejä voimakkaampaa aktivaatiota ohimolohkon etuosissa 300-400 ms aikaikkunassa. Tulokset valottavat abstraktien käsitteiden käsittelyn ajallista ja spatiaalista dynamiikkaa aivojen toiminnassa. Yhteenvetona voidaan todeta, että selvittämällä motoristen ja kielellisten aivoprosessien ajallisesti vaihtelevaa dynamiikkaa yllä kuvatut tutkimukset syventävät käsitystämme siitä, miten motorinen aivokuori edistää kielen ymmärtämistä, ja tuovat vaihtoehtoisia tulkintoja motorisen aivokuoren toiminnallisesta roolista kielen käsittelyssä.

Asiasanat: kielen käsittely, motorinen järjestelmä, fMRI, MEG, kielitaito, abstraktius

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Jyväskylä April, 16, 2023 Lili Tian

# LIST OF ORIGINAL PUBLICATIONS

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- II. Tian, L., Chen, H., Heikkinen, P., Liu, W., & Parviainen, T. (2023). The compensatory role of the motor cortex in the second language processing. *Neurobiology of Language*, 4(1), 178-197.
- III. Tian, L., Chen, H., Kujala, J., & Parviainen, T. (2023). Spatiotemporal dynamics of abstract concept processing: an MEG study. Submitted manuscript.

Taking into account the instructions given and comments made by the co-authors, the author of this dissertation contributed to the original publications as follows: she designed the experiments, collected the data, conducted the analyses, and wrote the manuscripts of the three publications.

# FIGURES

FIGURE 1	The Revised Hierarchical Model (adapted from Kroll &	
	Tokowicz, 2001)	.14
FIGURE 2	Schematic view of the experimental procedure (Study II)	.26
FIGURE 3	Activation maps of L1, L2 and contrasts between	
	L1 and L2 experiments	.31
FIGURE 4	Grand-averaged results and results of permutation tests	
	on source data.	.33
FIGURE 5	Grand-averaged cortical activation across conditions	
	from 150 ms to 500 ms	.35
	trom 150 ms to 500 ms	.35

# TABLES

TABLE 1	An exemplar of stimuli (Study II)	25
TABLE 2	Lexical properties and familiarity ratings of stimuli in	
	L1 and L2 (Study II)	25
TABLE 3	Results of cluster-based permutation F-tests on source data	
	(Study II)	34
TABLE 4	Results of cluster-based permutation F-tests on source data	
	(Study III)	35
TABLE 5	Summary of three studies	44

# CONTENTS

ABSTRACT TIIVISTELMÄ (ABSTRACT IN FINNISH) ACKNOWLEDGEMENTS LIST OF ORIGINAL PUBLICATIONS FIGURES AND TABLES CONTENTS

1	INT	IRODUCTION	13
	1.1	Conceptual representation and processing	14
		1.1.1 Bilingual conceptual representation and processing	14
		1.1.2 Abstract and concrete concept representation and	
		processing	15
	1.2	Neural basis of language understanding	16
		1.2.1 Classical and embodied views of language cognition	16
		1.2.2 Language network in the brain	17
		1.2.3 Motor cortex involvement in bilingual language	
		processing	
		1.2.4 Neural underpinnings of concrete, metaphorical, and	
		abstract concept processing	19
	1.3	Evaluations of previous studies	
	1.4	Aims of the research	
2	ME	THODS	23
_	2.1	Participants	
	2.2	Research ethics	
	2.3	Stimuli and procedure	
	2.4	fMRI and MEG data acquisition	
	2.5	Data analysis	
	2.6	Statistical analyses	
3	REC	SULTS	30
5	3.1	Study I	30
	3.1	Study I	
	3.3	Study III	
1	סות	CUSSION	36
4	11	The effect of abstractness on motor cortex involvement	
	4.1	The effect of language proficiency on motor cortex involvement	
	4.Z	Dual functional rale of the mater cortex in computing procession	ent 57
	4.3	an alternative hypothesis	11g. 20
	1 1	Spatiotomporal dynamics of abstract concent processing	
	4.4 4 E	Canceral discussion	40 11
	4.3	General discussion	

4.	.6	Limitations and future directions	45
YHTEI	ENV	VETO (SUMMARY)	46
REFER	REN	ICES	49

ORIGINAL PAPERS

# **1** INTRODUCTION

For a long time, language understanding has been assumed to involve languagerelated brain regions only, such as Broca's and Wernicke's areas. Over the past two decades, this view has been challenged by the embodied view of language cognition, which proposes that language understanding involves not only language domain-specific regions but also the motor system (Gallese & Lakoff, 2015; Pulvermüller, 2005; Zwaan, 2014). According to the embodied view, the motor system is involved in language understanding by means of simulating perceptual-based meanings conveyed by words. For instance, understanding the word *grasp* would spontaneously require mental simulation of the grasping action.

Neuroimaging and electrophysiological studies have provided evidence for the involvement of the motor system in language understanding (Buccino et al., 2018; Mollo et al., 2016; Vukovic et al., 2017). Moreover, evidence from clinical studies has also shed light on the importance of the motor system in language understanding. Individuals with motor deficits, such as Parkinson's disease (PD) and Huntington's Disease (HD), were found impaired in understanding actionrelated words (such as grasp, prick, kick, etc.), due to the motor dysfunction (Kühne et al., 2019; Monaco et al., 2019).

These studies have shed light on the importance of the motor system in language processing and deepened our understanding of the neural underpinnings of language processing. However, findings from previous studies have been mostly interpreted within the framework of embodied semantics, leading to a lopsided interpretation of the role of the motor cortex in language processing and the ignorance of other alternative interpretations or hypotheses (Mahon & Hickok, 2016). In addition, previous studies have rarely studied gradations of motor cortex involvement in different linguistic circumstances. Moreover, whether the motor system is differentially involved in the native and second language processing is also under-investigated.

Considering the above issues, this dissertation aims to investigate potential gradations of motor cortex involvement influenced by language proficiency and linguistic abstractness by using functional magnetic resonance imaging (fMRI)

and magnetoencephalography (MEG). Furthermore, the dissertation aims to explore the time-varying interplay between language and motor areas in processing language with varying abstractness in native and second languages.

### 1.1 Conceptual representation and processing

#### 1.1.1 Bilingual conceptual representation and processing

The question of whether native (L1) and second (L2) languages share the same conceptual representation in a bilingual brain has been extensively discussed. Most models of bilingual mental lexicon argue for a (partially) shared conceptual representation between L1 and L2 (see review by Francis, 2005; Kroll & Stewart, 1994). Moreover, it has been highlighted that multiple factors could potentially influence the extent to which conceptual representations overlap between L1 and L2, such as age of acquisition (AoA), language exposure, language distance, language proficiency, etc. (Costa & Sebastián-Gallés, 2014; Hämäläinen et al., 2017; van Hell & Tanner, 2012).

The acquisition of L1 lexicons usually engages the whole audio-visualmotor network, whereas the acquisition of L2 relies more strongly on the existing conceptual information mediated by L1 counterparts (or translation equivalents), especially for late second language learners (Kroll & Tokowicz, 2001; Kroll et al., 2010).

One of the most influential models of bilingual lexical representation is the Revised Hierarchical Model (RHM), which could be simplified as two asymmetries, i.e., asymmetry in the lexical link and asymmetry in the semantic or conceptual link between the two languages (FIGURE 1) (Kroll & Stewart, 1994; Kroll et al., 2010). According to the RHM, the lexical link from L2 to LI was stronger than that from LI to L2. In addition, the connection between the L2 lexical form and the conceptual information was weaker than that between the L1 lexical form and the conceptual information. The weaker conceptual representation of L2 is likely to result in delayed and more effortful semantic access and integration, compared with L1.



FIGURE 1 The Revised Hierarchical Model (adapted from Kroll & Tokowicz, 2001). The solid lines indicate stronger connections, and the dashed lines indicate weaker connections. The connection between the lexical form of L1 is assumed to be stronger than that of L2.

### 1.1.2 Abstract and concrete concept representation and processing

The way in which concrete and abstract concepts are represented and retrieved in our brain has long been an intriguing topic. Based on the classical definition of concepts, concepts associated with a perceptible and identifiable referent in the physical world are categorized as concrete concepts, such as *church*. In contrast, concepts lacking a directly perceptible referent in the physical world are classified as abstract concepts, such as *religion*.

It has been widely acknowledged across languages that concrete words are acquired earlier, easier, and faster than abstract words (Bergelson & Swingley, 2013; Borghi et al., 2017; James, 1975; Kroll & Merves, 1986; Paivio 1986; Schwanenflugel, 1991). The learning and processing advantage of concrete concepts over abstract concepts has been mainly accounted for by the dual code theory (DCT) (Paivio, 1991) and context availability theory (Schwanenflugel et al., 1992), which claim that concreteness may affect the representation and processing of concepts. According to the DCT, verbal and imaginal systems are utilized differently for the representation of concrete and abstract concepts. Abstract concepts, due to the lack of physical referent and the lower degree of imageability, are generally acquired and represented via linguistic associations in the verbal semantic system. Contrariwise, concrete concepts, due to their tangible referents in the physical world and higher degree of imageability, involve both verbal semantic system and visual-imagery system in coding. The dual coding mechanism is assumed to facilitate the processing of concrete concepts and lead to the processing advantage of concrete concepts over abstract ones. On the other hand, the context availability theory proposes that both abstract and concrete concepts are processed in the verbal semantic system. However, due to the stronger association with contextual information, concrete concepts are usually more easily and quickly processed compared with abstract ones.

Recent studies reflected on the classical definition by proposing that concrete and abstract concepts are not dichotomic and there is no clear cutoff between them (Barsalou et al., 2018; Binder, 2016; Borghi & Cimatti, 2009). As has been emphasized in Barsalou et al.'s (2018) study, "Artificial distinction of concrete and abstract concepts divided situated cognition into idealized bits and pieces of each type, omitting the critical dependence each has upon the other". The interdependence of concrete and abstract concepts implies that abstract concepts are not completely abstract, as they represent a means to collect a variety of sparse perceptual and situational experiences. Likewise, concrete concepts are not completely concrete, as they can be associated with abstract feelings or emotions depending on the context. In addition, compared with concrete concepts, the representation of abstract concepts is more dynamic over time and variable across communities, due to time-varying life experiences and different cultural values associated with the concepts.

The above discussions of conceptual representations necessitate neuroimaging studies to test and extend the assumptions concerning the representation of abstract and concrete concepts.

### **1.2** Neural basis of language understanding

### **1.2.1** Classical and embodied views of language cognition

Based on the **classical** (or disembodied) view on language representation, language is represented as abstract and amodal symbols in language-specific modules in our brain, such as Broca's and Wernicke's areas (Collins & Loftus, 1975; Fodor, 1983; Newell & Simon, 1972). According to the classical view, language processing involves predominantly left-lateralized frontal-temporal areas and is independent of the sensorimotor system.

The **embodied** view of language cognition argued against the modular view by proposing that language cognition needs to be considered in the context of body-mind interaction (Barsalou et al., 2008; Gallese, 2005; Gallese & Lakoff, 2015; Fischer & Zwaan, 2008; Pulvermüller & Fadiga, 2010). Based on the embodied view, language symbols are functionally and anatomically grounded in the sensorimotor system, which is used for mentally simulating sensorimotor-related meaning in language understanding (Kiefer & Pulvermuüller, 2012). According to the embodied view, semantic processing (i.e., processing of meaning) involves not only classic language-related brain areas but also the sensorimotor system to simulate perceptual-related meanings conveyed by words (Barsalou, 2008; Fischer & Zwaan, 2008; Gallese & Lakoff, 2015; Pulvermüller & Fadiga, 2010; Zwaan, 2014).

Studies using neuroimaging and electrophysiological techniques have provided evidence for embodied semantic processing by showing neural activation and oscillation in the motor cortex in semantic processing (Fargier et al., 2012; Fernandino et al., 2013; Klepp et al., 2014, 2015; Mollo et al., 2016; Moreno et al., 2013). Clinical studies of individuals with motor dysfunctions (e.g., Parkinson's disease) or with lesions in the motor cortex have brought relatively direct evidence for the engagement of the motor system in semantic processing (Buccino et al., 2018; Cardona et al. 2014; Desai et al., 2015; Fernandino et al., 2013; Kargieman et al., 2014; Kemmerer et al., 2012; Monaco et al., 2019; Pulvermüller & Fadiga, 2010). These investigations have found that participants with motor dysfunctions showed selective difficulty in processing words with an actionrelated meaning (e.g., kick), manifested as a reduced accuracy rate and a lack of modulation of motor responses among individuals with motor dysfunctions, in contrast with the control group. The association between impaired motor functions and difficulties in processing action-related words suggested a functional role of the motor system in language understanding.

However, controversial findings have also been reported concerning the functional role of the motor cortex in language understanding. Some brain lesion studies failed to show a causal relation between motor impairments and difficulties in processing words with action-related meanings (Maieron et al., 2013; Papeo et al., 2010). Controversial findings also came from studies exploring the Action-sentence Compatibility Effect (ACE) (Glenberg & Kaschak, 2002). Previous studies using the ACE paradigm have shown a facilitatory effect of

bodily motion on the processing of sentences describing the same direction, suggesting a functional role of the motor system in meaning processing (Glenberg et al., 2008; Kaschak & Borreggine, 2008; Santana & de Vega, 2011; Zwaan & Taylor, 2006). However, some recent studies failed to reproduce the facilitatory effect of bodily motion on the processing of action-related meanings (Greco, 2021; Morey et al., 2022; Papesh, 2015). In addition, more neuroimaging studies failed to show evidence for the assumption that the motor system plays a significant role in processing action-related concepts (Watson et al. 2013; see review by Caramazza et al., 2014).

### **1.2.2** Language network in the brain

Language network refers to a set of brain regions jointly involved in language processing. Previous studies and meta-analyses involving fMRI and PET techniques have provided insights into the neural architecture of language cognition, which mainly includes left-lateralized posterior inferior parietal lobe, anterior, middle and superior temporal lobe, inferior frontal cortex and dorsomedial prefrontal cortex (Binder et al., 2009; Carreiras et al., 2013; Lehtonen et al., 2005; Price, 2012; Rapp et al., 2012). Current neuroimaging studies, by using MEG, have further provided temporal dynamics of the involvement of individual subregions in the language network in reading. It has been generally observed that the reading trajectory started with early robust activation in the bilateral occipital areas, followed by left-lateralized neural activities flowing from posterior to anterior temporal and frontal areas (Brennan & Pylkkänen, 2012; Dhond et al., 2007).

Among the language-related region mentioned above, the ATL has been assumed to serve as the semantic-hub, which integrates multi-modal concepts distributed in the domain-specific brain regions (Lambon Ralph et al., 2017; Patterson & Lambon Ralph, 2016; Patterson et al., 2007; Rogers et al., 2004). In addition, the ATL has been assumed as the key region for processing domaingeneral semantic information but with a bias towards abstract social concepts, such as emotion, theory of mind and moral concepts (see review by Wong & Gallate, 2012; Ross & Olson, 2010; Zahn et al., 2007).

In a recent review by Fedorenko & Thompson-Schill (2014), it was proposed that the language network should not only include core language areas but also domain-general areas, i.e., brain regions that are not functionally specialized for language processing but coactivate with core language areas during language processing. The domain-general areas, such as the cognitive control network, may not directly contribute to linguistic processing but play a supportive role in achieving successful language understanding.

### 1.2.3 Motor cortex involvement in bilingual language processing

In light of embodied cognition, language understanding involves not only language-related brain regions but also the motor system (Barsalou, 2008; Kiefer & Pulvermüller, 2012).

So far, the involvement of the motor cortex has been mostly discussed within native languages (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). These studies provided consistent evidence for the engagement of the motor cortex in native language processing, indicated by neural activation in the motor cortex, motor evoked potentials (MEPs), and desynchronization of frequency bands associated with motor imagery. Meanwhile, some studies revealed a dissociation between the impairment of the motor cortex and the difficulty of processing action-related meanings (Maieron et al., 2013; Papeo et al., 2010). By employing fMRI, Maieron et al. (2013) explored functional connectivities between the language area (left inferior frontal gyrus) and the primary motor cortex in an action-verb naming task performed by participants with lesions in the primary motor cortex and healthy control participants. Results revealed a lack of task-modulated functional coupling between the language area and the primary motor cortex for both groups. These findings suggested that the involvement of the motor cortex may not be strictly related to the processing of action-related meaning.

In contrast, only few studies have investigated the engagement of the motor system in second languages (L2) (Birba et al., 2020; De Grauwe et al., 2014; Monaco et al., 2021; Vukovic & Shtyrov, 2014; Xue et al., 2015; Zhang et al., 2020). In Vukovic and Shtyrov's (2014) study, the event-related desynchronization (ERD) of mu-rhythm (8–12 Hz, 14–20 Hz), which has been frequently used as an index of motor cortex involvement, was found in both L1 (German) and L2 (English) among German-English bilingual participants, with the ERD greater for L1 than L2. The greater ERD for L1 was suggested to indicate a greater extent of embodiment in L1. Nevertheless, in Monaco et al.'s (2021) study, greater motor excitability was found for L2 (English) than L1 (French) in a semantic judgment task involving action-related words, manifested as greater motor evoked potentials for L2 when transcranial magnetic stimulation (TMS) was applied 275 ms after target onset. The above studies have shed light on the differential involvement of the motor cortex in L1 and L2 processing.

On the other hand, similar strength of activation in the motor cortex has been observed in **De Grauwe** et al.'s (2014) study, where L1 (native speakers of Dutch) and L2 (advanced German learners of Dutch) groups were asked to perform a lexical decision task involving action-related and non-action-related words. The similar degree of activation in the motor cortex was assumed to suggest that the L2 semantic representation for advanced L2 speakers was rich enough to elicit a similar degree of motor responses as native L1 speakers. The controversial findings necessitate further studies on the involvement of the motor system in second language processing.

# **1.2.4** Neural underpinnings of concrete, metaphorical, and abstract concept processing

A growing body of research has revealed activation in the motor cortex during reading words related to bodily motion, especially for literal language (e.g., *catch* the ball) (Dalla Volta et al., 2014; Desai et al., 2013; 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; Pulvermüller et al., 2005; Tettamanti et al., 2005).

Metaphorical language, which expresses abstract meaning via concrete word form, serves as an intermediate level of abstractness to explore how the motor cortex is differentially involved in processing language with graded abstractness. By employing fMRI, some studies revealed activation in motor regions in processing metaphorical language (e.g., *catch* the meaning) (Bardolph & Coulson, 2014; Boulenger et al., 2009; Cacciari et al., 2011; Desai et al., 2010, 2013; Raposo et al., 2009). These studies provided evidence for the engagement of the motor cortex in the processing of action-related concepts at the metaphorical level. However, some other studies, by using fMRI and EEG, reported no signs of the engagement of the motor cortex during comprehending action-related metaphorical language (Aziz-zadeh et al., 2006; Raposo et al., 2009; Desai et al., 2010, 2013; Bardolph & Coulson, 2014).

In contrast to the literal and metaphorical language, few studies have investigated the involvement of the motor system in abstract language processing (e.g., *understand* the meaning). The very limited amount of research concerning abstract concepts might be attributed to the lack of physical referents of abstract concepts, which makes them less likely to evoke motor-related response, compared with concrete concepts (Borghi et al., 2017). Current findings concerning abstract concepts are rather inconsistent, with some studies showing the involvement of the motor system in abstract language processing (Harpaintner et al., 2020; Hultén et al., 2021), while some other studies failed to show such involvement (Cacciari et al., 2011; Dalla Volta et al., 2014; Desai et al., 2010, 2013).

Studies have also explored gradations of motor cortex involvement by using stimuli following a hierarchical order of abstractness, including actionrelated literal (or concrete) words, action-related metaphorical words, and abstract words (Desai et al., 2013; Schaller et al., 2017). In Desai et al.'s (2013) study, the BOLD (blood oxygen level dependent) signals revealed a linear trend of attenuated activation in the motor cortex with the increase of abstractness, manifested as the strongest activation for action-related literal words, medium activation for action-related metaphorical words and the weakest activation for abstract words. Similar results have also been found in Schaller et al.'s (2017) study, where stronger ERD in the beta frequency band (16–25 Hz) was found for action-related\_concrete and metaphorical sentences than abstract ones, indicating a greater degree of motor cortex engagement in processing action-related language than abstract language.

Concerning the involvement of the language network, abstract concepts were found to involve a greater extent of the classical language regions than concrete concepts, including left-lateralized inferior frontal gyrus (IFG), anterior temporal lobe (ATL), middle temporal, and posterior temporal regions (Binder et al., 2005; Desai et al., 2013; Fiebach & Friederici, 2004; Noppeney & Price, 2004; Pobric et al., 2009; Rodríguez-Ferreiro et al., 2011; Sabsevitz et al., 2005; Sakreida et al., 2013; see meta-analysis by Wang et al., 2010). In Sabsevitz et al.'s (2005) study, fMRI was employed to explore the neural underpinnings of concrete and abstract word processing during a semantic similarity judgment task. Results showed greater activation for concrete words (relative to abstract words) in the bilateral multimodal network, including ventral temporal and posterior-inferior parietal areas. On the other hand, results showed greater activation for abstract words (relative to concrete words) in the left-lateralized semantic network, including superior temporal and inferior frontal areas. The results suggested distinctive neural representations of concrete and abstract words, with the former being more perceptual-based and the latter being more linguistic-based.

M/EEG recordings have been employed to further explore the temporal dynamics of neuronal activities in the processing of concrete and abstract concepts (Dhond et al., 2007; Holcomb et al., 1999; West & Holcomb, 2000). In Dhond et al.'s (2007) study, greater activation was found in the left fronto-temporal area for concrete than abstract words at 330 ms post-stimulus (peak at 400 ms). The decreased activation for abstract words was interpreted as reflecting the more extensive semantic network of abstract words, compared with concrete words. In addition, at 550 ms, greater activation in the right occipito-parietal area was found for concrete words than abstract words, which suggested a perceptual-based representation of concrete words.

### **1.3** Evaluations of previous studies

Over the past two decades, accumulative neuroimaging and electrophysiological studies have provided evidence for the engagement of the motor cortex in semantic processing. These investigations have deepened our understanding of the neurobiological bases of language processing by emphasizing the important role of the motor system in language processing. Although these studies have updated our knowledge of how language is possibly processed in our brain, some key issues concerning the involvement of the motor cortex in language processing have not been thoroughly studied.

Firstly, previous studies are primarily limited to provide an all-or-none answer to the question of whether the motor system is involved in semantic processing. The discussion on embodiment/disembodiement (or modal/amodal) dichotomy may hinder our understanding of how the motor cortex is involved in language understanding (Michel, 2021). In contrast, it would be more constructive to give a more-or-less answer to the question of how the motor cortex is differentially engaged in different contexts (i.e., gradations of embodiment) (Chatterjee, 2010; Meteyard et al., 2012).

Secondly, earlier studies employing fMRI, TMS, or EEG lacked either temporal or spatial resolution in measuring brain activities. Combining temporal and spatial information is fundamental for understanding *when* and *how* the language and motor networks are involved and coordinated in language understanding. It would be more informative to introduce neuroimaging techniques, such as MEG, to study spatio-temporal dynamics in language processing.

Thirdly, misconceptions of reverse inference (Henson, 2006; Poldrack, 2006) can be found in some previous studies, which may lead to the lopsided interpretation of motor cortex activation and the ignorance of alternative interpretations or hypotheses (Mahon & Hickok, 2016). In the previous studies, activation in the motor cortex has been mostly interpreted as the engagement of the motor cortex for the mental simulation of action-related meanings. However, the engagement of the motor cortex is not necessarily for mental simulation of action-related meanings but might be ubiquitous in cognitive processes on a general level (Kukleta et al., 2016; Meteyard et al., 2012).

Lastly, previous studies mainly focused on the involvement of the motor system in native languages, with second languages rarely being studied (De Grauwe et al., 2014; Vukovic and Shtyrov, 2014).

## **1.4** Aims of the research

Considering the issues mentioned above, this dissertation aims to investigate potential gradations of motor cortex involvement modulated by language proficiency and linguistic abstractness. Furthermore, the dissertation aims to explore the time-varying interplay between language and motor areas in processing language with varying abstractness in the native and second language.

By using fMRI with high spatial resolution, **Study I** aims to explore potential gradations of motor cortex involvement manipulated by language proficiency (L1: native language, L2: second language) and abstractness (literal, metaphorical, and abstract). Specifically, Study I aims to answer the following questions: (1) To what extent is the motor cortex involved in the processing of literal, metaphorical, and abstract phrases? (2) To what extent is the motor cortex involved in the processing of L1 and L2? In light of the graded abstractness of literal, metaphorical, and abstract language, it is hypothesized that the magnitude of activation in the motor cortex might follow a hierarchically decreasing order, with the greatest activation for the literal, the medium for the metaphorical, and the lowest activation for the abstract language. Besides, based on the assumption that the lexical representation of a less proficient language involves less multi-modal information, it is hypothesized that the processing of L2 may require less motor cortex involvement for the mental simulation of action-related meanings, compared with that of L1. **Study II** aims to investigate temporal dynamics of activation in language and motor regions in L1 and L2 processing by using magnetoencephalography (MEG) with millisecond temporal and sub-centimeter spatial resolution. Specifically, Study II aims to explore *whether* and *when* the involvement of motor and language areas is affected by language proficiency (L1 and L2) and abstractness (literal, metaphorical, and abstract). Study II is semi-exploratory in nature, which aims to replicate and extend the findings from Study I by scrutinizing the temporal activation patterns of language and motor areas.

**Study III,** by employing MEG recordings, aims to investigate the timevarying involvement of language and motor areas in abstract concept processing in the native language. Specifically, the study aims to explore *whether* and *when* the language areas are differentially involved in processing language with different levels of abstractness (i.e., abstract, metaphorical, and concrete) with regard to timing and magnitude of activation. Meanwhile, the study aims to investigate *whether* and *when* the motor areas are differentially involved in processing language with different levels of abstractness.

## 2 METHODS

### 2.1 Participants

In **Study I**, 29 participants (11 male, 18 female) were recruited from Dalian University of Technology, China. In **Study II** and **III**, 26 participants (8 male, 18 female) were recruited from the University of Jyväskylä, Finland. All participants were Chinese-English speakers with Chinese as their native language and English as their second language. All participants were right-handed and had a normal or corrected-to-normal vision, without a self-reported history of neurological or psychiatric diseases. In Study I, one participant was excluded from data analysis due to uncorrectable head motion, resulting in 28 participants for further analysis. In Study II and III, two participants were excluded from data analysis due to the low accuracy rate in behavioral performance, resulting in 24 participants for further analysis.

### 2.2 Research ethics

The three studies were conducted in accordance with the ethical principles of the Declaration of Helsinki. **Study I** was reviewed and approved by the Ethics Committee of Dalian University of Technology and Affiliated Zhongshan Hospital of Dalian University. **Study II and III** were reviewed and approved by the Ethics Committee of the University of Jyväskylä. Informed consent was obtained from participants prior to the participation, and compensations were paid to participants after the completion of the experiment.

Data of **Study I** were archived in the server of the Department of Radiology, Affiliated Zhongshan Hospital of Dalian University. Data of **Study II** and III were archived in the server of the University of Jyväskylä. Direct identifiers were anonymized or removed. The data were accessible only to the members of the research group. All data were processed confidentially in compliance with the data protection legislation. The data are not publicly available due to the restrictions of research ethics stated in the Privacy Notice for Research Subjects. The data that support confirming or verifying the validity and authenticity of the results are available upon reasonable request from the corresponding author and the first author of the three studies.

### 2.3 Stimuli and procedure

Study I included L1 and L2 experiments, which shared the same procedure and the stimuli of which were virtually semantic correspondent. Stimuli in each experiment consisted of 120 verb phrases (40 for the literal condition, 40 for the metaphorical condition, and 40 for the abstract condition). An action-related verb (related to arm or hand) was embedded in both literal (抓住皮球/catch the ball) and metaphorical (抓住意思/catch the meaning) conditions. The abstract condition connoted the same meaning as the metaphorical one (理解意思/understand the meaning). The verb phrases in both L1 and L2 experiments shared the same syntactic structure: verb + object.

Similar to Study I, **Study II** consisted of L1 and L2 experiments. Each experiment consisted of 180 verb phrases (60 for the literal condition, 60 for the metaphorical condition, and 60 for the abstract condition) (TABLE 1). Lexical properties and familiarity ratings (1: not familiar at all; 5: very familiar) were conducted to ensure that stimuli properties did not differ significantly across conditions in L1 and L2 (ps > .05). Motor-relatedness of all stimuli was evaluated on a 5-point scale (1: not related at all; 5: very related) (TABLE 2). Trials were shown in a pseudo-randomized order. Each trial consisted of two verb phrases. The first verb phrase shared the same feature with stimuli described in Study I. The second verb phrase was either semantically congruent or incongruent with the first phrase. The L1 stimuli subtended a horizontal visual angle of 3° 5', and the L2 stimuli subtended a horizontal visual angle of 4° 58'.

**Study III** only included the L1 experiment, consisting of 180 verb phrases (60 each condition). The feature of stimuli is identical to Study II.

	L1 (Chinese)	L2 (English)
1:4	抓住皮球 — 握住皮球 (con)	catch the ball — get hold of the ball (con)
literal	抓住皮球 — 松开皮球 (incon)	catch the ball — lose the ball (incon)
	抓住意思 — 领悟意思	catch the meaning — comprehend the meaning
metaphorical	抓住意思 — 忘记意思	catch the meaning — forget the meaning
abstract		understand the meaning — get the meaning
	理解意思 — 曲解意思	understand the meaning — distort the meaning

TABLE 1An exemplar of stimuli in L1 and L2 (Study II)

(The L1 and L2 stimuli are semantically equivalent. Con: semantically congruent; Incon: semantically incongruent.)

TABLE 2 Lexical properties and familiarity ratings of stimuli in L1 and L2 (Study II)

		word length (mean±SD)	number of strokes/letters	familiarity	motor- relatedness
L1	literal	$4 \pm 0.00$	$34.03 \pm 6.51$	$4.97\pm0.18$	$4.60\pm0.40$
	metaphorical	$4 \pm 0.00$	$33.37 \pm 5.85$	$4.43 \pm 0.73$	$2.78 \pm 1.24$
	abstract	$4 \pm 0.00$	$34.83 \pm 6.26$	$4.83\pm0.46$	$2.12 \pm 1.23$
L2	literal	$3.07 \pm 0.45$	12.53 ± 2.22	$4.87 \pm 0.35$	$4.39 \pm 0.58$
	metaphorical	$3.13 \pm 0.35$	$13.97 \pm 2.34$	$4.07\pm0.76$	$2.64 \pm 0.96$
	abstract	$2.97\pm0.18$	$15.9 \pm 1.99$	$4.37\pm0.76$	$2.11 \pm 1.04$

In **Study I**, the L1 experiment was presented after the L2 experiment. Trials were displayed in a pseudo-randomized order. Each trial began with a 2000 ms fixation located at the center of the screen. Afterwards, a verb phrase was displayed for 2000 ms, followed by a blank screen for 2-8s. Participants were instructed to read phrases during the scanning session and evaluate the degree of motor-relatedness of the phrases after the scanning session.

In **Study II**, as shown in FIGURE 2, each trial started with a central fixation (500 ms), followed by a blank screen (500 ms). Then, the first phrase was presented (1500 ms) followed by a blank screen (1000 ms), after which the second phrase was presented (1500 ms) followed by "?" for a maximum of 3000 ms. Participants were required to judge the semantic congruency of the two phrases upon the appearance of "?" by pressing response buttons. Only the first verb phrase, which was independent of task-related strategic manipulations, was used for further MEG analysis.

Study III shares the same experimental procedure as Study II.



FIGURE 2 Schematic view of the experimental procedure (Study II)

### 2.4 fMRI and MEG data acquisition

In **Study I**, fMRI data were recorded using a 3T Siemens Tim Trio magnetic resonance scanner at Affiliated Zhongshan Hospital of Dalian University, China. The scanning session consisted of four parts: resting-state (6'08"), language experiment (28'28"), motor localizer task (3'08") and T1-weighted images (5'43"). In the language experiment session, participants were asked to take 2 minutes' 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: 4mm, voxel size:  $3.5 \times 3.5 \times 3.5 \text{ mm}^3$ , flip angle: 90 degree, TR: 2000ms, TE: 30ms. Volumes are composed of 32 axially oriented 4-mm slices with a 1 mm interslice gap. Structural T1-weighted 3D images of the whole brain were obtained with 1×1×1 mm<sup>3</sup> voxel dimensions at the end of the scanning session.

In **Study II** and **III**, MEG data were recorded using a 306-channel (102 magnetometer channels and 204 planar gradiometer channels) whole-head MEG system (TRIUX MEG system, MEGIN Oy, Helsinki, Finland) in a magnetically shielded room at the Centre for Interdisciplinary Brain Research, the University of Jyväskylä, Finland. Five head-position indicator (HPI) coils were attached to each participant's head surface, with three on the forehead and one behind each ear, to track the head position of each participant. Electrooculography (EOG) signals were recorded from four electrodes located near the corner of the left/right eye and above/below the right eye. One ground electrode was attached to the clavicle. Three fiducial landmarks (nasion, left and right preauricular points) and around 120 head points were digitized to build a head coordinate system for the co-registration to the MRI template. MEG signals were recorded at a sampling rate of 1000 Hz with an online band-pass filtering of 0.1–330 Hz.

## 2.5 Data analysis

In **Study I**, data pre-processing was done with DPABI (rfmri.org/dpabi). Functional images were slice-time corrected to the middle slice, realigned to the first image of the run, registered into the MNI152 standard space template, rescaled to  $3\times3\times3$  mm<sup>3</sup> resolution, and smoothed with a FWHM 6 mm Gaussian kernel. In the temporal domain, detrend and band-pass filtering (0.01mHz - 150mHz) were applied to remove the system interference and abnormal frequency components.

Individual-level and group-level analyses were performed in SPM12 software (www.fil.ion.ucl.ac.uk/spm/software/spm12). Contrast analyses between conditions (literal vs. metaphorical, literal vs. abstract, and metaphorical vs. abstract) and between language (L1 vs. L2) were performed. Psychophysiological interactions analyses (PPI, Friston et al., 1997) were performed to estimate the correlation of time series between language and motor ROIs across the three conditions. Software packages of DPABI and BrainNet View were used for image inspection and visualization.

Language and motor ROIs were defined in a hybrid way by integrating data-driven estimates (based on activation maps) and results from the previous meta-analysis. The above procedure resulted in language ROIs, including posterior inferior parietal lobe, middle temporal gyrus, inferior frontal gyrus, and angular gyrus; motor ROIs, including precentral cortex, supplementary motor area, and premotor cortex.

**Study II** and **III** shared the same procedure of pre-processing and source estimation. Firstly, the temporal extension of signal space separation (tSSS) was applied to the raw data to reduce external magnetic interference and withinsensor artifacts (Taulu & Kajola, 2005) and tSSS-based head movement compensation was performed in MaxFilter GUI (version 2.2; MEGIN Oy, Helsinki, Finland).

Pre-processing of MEG data was performed using Meggie, a graphical user interface based on MNE-Python (Gramfort et al., 2013). First, data segments contaminated by artifacts were identified through visual inspection and excluded from further analyses. Afterwards, MEG data were downsampled to 250 Hz, with a lowpass filter of 40 Hz. Temporal ICA (Independent component analysis) was applied to reduce physiological artifacts related to heartbeats, blinks, and saccades. MEG data were then segmented into epochs 200 ms before and 1000 ms after the onset of the first verb phrase. The 200 ms interval prior to the onset of the first phrase was used as a baseline. Epochs (combined of both congruent and incongruent trials) were then averaged to obtain the event-related fields for each condition (concrete, metaphorical, and abstract) and for each participant.

Source localization was done in MNE-Python (Gramfort et al., 2013). Cortical surface reconstruction and volumetric segmentation were performed using the CN200 template (Yang et al., 2020). Coregistration was performed for each participant by aligning the template MRI scalp with digitization points on the scalp surface using three-dimensional scaling. Dynamic statistical parametric mapping (dSPM) (Dale et al., 2000) was used as the inverse method to compute the normalization of estimates using the noise covariance matrix. Individual source estimates were then morphed to the same template brain (CN200).

In both Study II and III, ROIs were selected in a hybrid manner by referring to the spatial distribution of cortical activation and by referring to the findings of earlier meta-analyses of fMRI studies related to semantic processing (for language ROIs selection) and motor performance/imagery (for motor ROIs selection). Brain areas appearing in both previous meta-analyses and dataderived brain activation maps were chosen as ROIs based on the Destrieux Atlas a2009s (Destrieux et al., 2010). The above procedure resulted in the following ROIs in Study II: language ROIs: short insular gyri (partially overlapping with inferior frontal gyrus), planum polare of superior temporal gyrus (part of anterior temporal cortex), and superior temporal sulcus; motor ROIs: inferior part of precentral sulcus and central sulcus (part of primary motor cortex). Study III shared the same language and motor ROIs as Study II. However, due to the long area of the superior temporal sulcus and the central sulcus, these two ROIs are split into smaller parcels respectively by employing a similar procedure as Ala-Salomäki et al. (2021). The splitting resulted in two smaller ROIs, i.e., posterior part of superior temporal sulcus and inferior part of central sulcus. The splitted ROIs are used for further statistical analyses for Study III.

In **Study II**, time-windows were selected based on the latency of peak activities in the grand-averaged sensor waveform and the corresponding time-resolved source activation maps, which resulted in the two time-windows of 300-500 ms and 600-800 ms. These two time-windows were used for further statistical analysis. In **Study III**, the time-window was constrained to 200-500 ms. This time-window is within the typical latency range of the N400 response related to semantic processing, as suggested by previous M/EEG studies (see reviews by Kutas & Federmeier, 2011; Lau et al., 2008). The time-window showed also clear activation in the frontal-temporal areas in the present study. Statistical analyses were performed over a 100 ms time-window from 200-500 ms, i.e., 200-300, 300-400, and 400-500 ms.

### 2.6 Statistical analyses

In **Study I**, statistical analyses were conducted by using the general linear model (GLM) and hemodynamic response function (HRF) in SPM12 software. GLM and HRF were applied to evaluate the activation of brain regions of interest. Activation maps of individual conditions (literal, metaphorical, and abstract) were calculated (GRF corrected, voxel value *p*<.05, cluster inclusion threshold  $\alpha$  =0.05, voxel size>30). Afterwards, contrast analyses between conditions (literal> metaphorical, literal>abstract, metaphorical>abstract) were conducted by setting the contrast matrix in SPM12.

In **Study II**, Statistical analysis was performed on the amplitude of source waveforms (represented as dSPM value) extracted from each ROI for TW1 and TW2, respectively. To examine the effect of language proficiency and abstractness, we conducted cluster-based permutation F-tests in MNE-Python. Cluster-based permutation tests across time and space were applied to address the multiple comparison problem (Maris & Oostenveld, 2007). Statistical significance was computed by running the permutation test up to 1000 times,  $\alpha = 0.05$  for cluster inclusion and  $\alpha = 0.05$  for permutation significance. FDR correction (Benjamini-Hochberg False Discovery Rate) (Benjamini & Hochberg, 1995) was applied to the resulting *p*-values across language ROIs and motor ROIs for multiple testing.

**Study III** had a similar statistical analysis procedure to Study II. To investigate the effect of abstractness. Nonparametric permutation F-tests with spatiotemporal clustering were conducted for each language and motor ROI over a 100 ms time-window from 200-500 ms following the onset of the first verb phrase (200-300, 300-400 and 400-500 ms). Study III employed the same statistical parameters as Study II in terms of significance criterion and multiple comparison correction.

## 3 RESULTS

### 3.1 Study I

By adopting fMRI, **Study I** explored the effect of language proficiency (L1/L2) and linguistic abstractness (literal, metaphorical, and abstract) on the neural activation of motor areas in semantic processing.

In the L1 Experiment, GLM analyses were performed for individual conditions. In terms of the motor ROIs, significant BOLD responses were found across conditions in BA6 (supplementary motor area, SMA) (FIGURE 3a). Significant activation was also found in BA4 (precentral gyrus; SMA) only for the literal condition. Contrast analyses between conditions (literal vs. metaphorical, literal vs. abstract, and metaphorical vs. abstract) revealed gradually decreasing BOLD responses from the literal to the abstract condition in the motor ROIs, including BA4 (precentral gyrus) and BA6 (SMA) (FIGURE 3a).

In the L2 experiment, GLM analyses of individual conditions indicated significant BOLD responses in the motor ROIs, including BA6 (SMA) and BA4 (precentral gyrus; SMA) (FIGURE 3b). Contrast analyses between conditions revealed attenuated activation in the motor ROIs following a similar hierarchical order (literal < metaphorical < abstract) (FIGURE 3b).

Contrast analyses between L1 and L2 revealed overall greater activation in the motor ROIs for L2 than L1, as shown in FIGURE 3c. Specifically, results showed greater activation for L2 than L1 in BA4 (precentral gyrus) and BA6 (precentral gyrus) for the literal condition and greater activation for L2 than L1 in BA6 (precentral gyrus) for both metaphorical and abstract conditions.

PPI analyses were conducted to explore functional connectivity between language and motor ROIs with seed regions of BA45 (language ROI) and BA6 (motor ROI). For the L1 experiment, results showed a hierarchically increasing strength of functional connectivity with the increase of abstractness (literal < metaphorical < abstract). In contrast, PPI analyses for the L2 experiment revealed a hierarchically decreasing order of functional connectivity strength with the increase of abstractness (literal>metaphorical>abstract).



FIGURE 3 Activation maps of L1, L2 and contrasts between L1 and L2 experiments. (a) Top row: Activation maps of individual conditions in the L1 experiment. (GRF corrected, voxel value p<.05; cluster-level threshold  $\alpha$ =0.05, voxel size>30). Bottom row: Activation maps of between-condition contrasts in the L1 experiment (uncorrected, p<.05, voxel size>30). (b) Top row: Activation maps of individual conditions in the L2 experiment (GRF corrected, voxel value p<.05; cluster-level threshold  $\alpha$ =0.05, voxel size>30). Bottom row: Activation maps of between-condition contrasts in the L2 experiment (GRF corrected, voxel value p<.05; cluster-level threshold  $\alpha$ =0.05, voxel size>30). Bottom row: Activation maps of between-condition contrasts in the L2 experiment (uncorrected, p<.05, voxel size>30). (c) Activation maps of contrasts between L1 and L2 experiments. Circles in green indicated motor ROIs with significant activation; Circles in yellow indicated language ROIs with significant activation (uncorrected, p<.05, voxel size>30). L: Literal; M: Metaphorical; A: Abstract.

### 3.2 Study II

The grand-averaged waveform at the sensor level is shown in FIGURE 4a. Based on the visual inspection, four peaks were identified in the sensor waveform: Peak 1 at around 130 ms, Peak 2 at 260 ms, Peak 3 at 400 ms, and Peak 4 at 700 ms. At peak 3 (400 ms), a notably greater amplitude was shown for L1 than L2. A reversed pattern was found for peak 4 (700 ms), manifested as greater amplitude for L2 than L1.

Source estimation analyses showed a typical spatiotemporal pathway of visual word processing, starting from early robust activation in bilateral occipital areas, followed by left-lateralized activation flowing from posterior to anterior temporal and frontal areas (FIGURE 4b). In addition, source estimation results revealed neural activation in the motor areas across conditions (literal, metaphorical, and abstract) for both L1 and L2.

Cluster-based permutation F-tests on source data revealed a significant main effect of language proficiency in both language and motor ROIs (TABLE 3). Specifically, results indicated overall greater activation in the language ROIs (short insular gyri and planum polare of the superior temporal gyrus) for L1 than L2 in the latency range of 300-500 ms (FIGURE 4c). Furthermore, our results showed overall greater activation in the motor ROI (central sulcus) for L2 than L1 in the late latency range of 600-800 ms (FIGURE 4c). However, Study II failed to replicate the effect of abstractness as reported in Study I.



FIGURE 4 Grand-averaged results and results of permutation tests on source data. (a) Grand-averaged results at sensor level (204 gradiometers) across conditions in the L1 and L2 experiments; The light-shaded areas indicate the time window applied to the ROI-based statistical analysis. (b) Grand-averaged source activation quantified as mean dSPM value over time points corresponding to each peak. The intensity of the color in the cortical activation map indicates the degree of dSPM value. (c) Significant clusters at source space obtained from the cluster-based permutation F-tests and corresponding source time-courses (represented as dSPM value). The light orange shading area shows the time window of significant clusters.

	Deveslation Terminologia			<i>p</i> -values (FDR-corrected)					
	(Destrieux Atlas a2009s) A	Anatomica	#Vertice	300-500 ms			600-800 ms		
				A:B	Α	В	A:B	Α	В
Language ROIs	G_insular_short	Short insular gyri	732	0.095	0.042*	0.258	0.243	0.970	0.240
	G_temp_sup-Plan_polar	Planum polare of the superior temporal gyrus	876	0.215	0.042*	0.258	0.406	0.613	0.290
	S_temporal_sup	Superior temporal sulcus	5216	0.095	0.326	0.271	0.298	0.842	0.451
Motor ROIs	S_precentral-inf-part	Inferior part of the precentral sulcus	1587	0.056	0.466	0.859	0.465	0.056	0.246
	S_central	Central sulcus	3139	0.073	0.515	0.512	0.465	0.020*	0.246

#### TABLE 3 Results of cluster-based permutation F-tests on source data (Study II)

(**A:B**: interactions between language proficiency and linguistic abstractness; **A**: main effect of language proficiency; **B**: main effect of abstractness. Statistical significance (p < .05) is marked in bold with an asterisk.)

### 3.3 Study III

Grand-averaged results (FIGURE 5) at the source level showed that, at around 250ms, concrete and metaphorical phrases evoked robust activation in the posterior part of superior temporal sulcus (STS), which was delayed for the abstract ones until 350 ms. In the anterior temporal pole (TP), clear activation was observed for the abstract phrases from 350 ms onwards, which was attenuated for the metaphorical ones, and virtually absent for the concrete ones. Activation in the inferior part of central area can be observed in the 350-400 ms across conditions.

Cluster-based permutation tests were conducted at the source level for each language and motor ROI in the three consecutive latency ranges (200-300, 300-400, and 400-500 ms). As shown in TABLE 4, compared with concrete and metaphorical phrases, abstract phrases evoked significantly weaker activation in the left posterior STS in the latency range of 200-300 ms and significantly stronger activation in the left anterior TP in the latency range of 300-400 ms. Results showed no significant difference in the involvement of motor ROIs across conditions.



FIGURE 5 Grand-averaged cortical activation across conditions from 150 ms to 500 ms. The intensity of the colour indicates the degree of dSPM values. Con: concrete; met: metaphorical; abs: abstract.

#### TABLE 4 Results of cluster-based permutation F-tests on source data (Study III)

	Parcellation	Terminologia	<i>p</i> -values (FDR-corrected) time-window (ms)			
	(Destrieux Atlas a2009s)	Anatomica	200-300	300-400	400-500	
	G_insular_short	Short insular gyri	.770	.082	.150	
Language ROIs	G_temp_sup-Plan_polar	Planum polare of superior temporal gyrus	.128	.071	.401	
	S_temporal_sup_sub3	Posterior part of superior temporal sulcus	.032	.257	.223	
	Pole_temporal	Temporal pole	.313	.017	.164	
Motor ROIs	S_precentral-inf-part	Inferior part of the precentral sulcus	.159	.186	.346	
	S_central_sub1	Inferior part of central sulcus	.538	.262	.171	

(Statistical significance p < .05 is represented in bold.)

## 4 DISCUSSION

### 4.1 The effect of abstractness on motor cortex involvement

**Study I** explored potential gradations of motor cortex involvement in processing language with varying abstractness, i.e., literal, metaphorical, and abstract language. Results showed hierarchically attenuated activation in the motor areas with the increase of abstractness in both L1 and L2, manifested as the greatest activation for the literal, followed by the metaphorical, and the weakest for the abstract language.

The results were consistent with previous studies showing the involvement of the motor (or sensorimotor) cortex in processing both action-related and abstract words (Dreyer & Pulvermüller, 2018; Guan et al., 2013; Vukovic et al., 2017). These findings consistently showed that the involvement of the motor system is ubiquitous in semantic processing, regardless of the abstractness property of language. In addition, the decremental tendency of motor cortex involvement was also found in Desai et al.'s (2013) study, where the reliance on the motor system decreased with the increase of abstractness.

In Study I, despite the similar pattern of activation in L1 and L2, neural activation for the metaphorical language was different between L1 and L2. Specifically, metaphorical language is processed more similarly to literal language in L1 and more similar to abstract language in L2. This divergence might be due to the fact that metaphorical concepts are learned differently in L1 and L2. In L1, the acquisition of metaphorical expressions is largely built upon the literal meaning, which evolves from rich perceptual and multi-modal information. The association with literal meaning is likely to contribute to the preservation of the literal component in metaphorical concept representation. In addition, as a logographic language, all hand- or arm-related action verbs in Chinese consist of the radical part  $\ddagger$ , indicating that the characters are related to
hand or arm movement. This semantic clue may also contribute to similar activation strength for the metaphorical and literal language. In contrast, metaphorical expressions in L2 are usually learned via L1 translation equivalents, with their literal meaning being devoured by abstract translation. The heavy reliance on abstract meaning is likely to contribute to the similar degree of motor cortex involvement for metaphorical and abstract language.

However, **Study II**, by employing MEG, failed to replicate the effect of abstractness on the involvement of the motor cortex, indicating that neural responses in the motor cortex might not be influenced by the abstractness of language. The inconsistent findings from Study I and II might be due to the sensitivity of analysis methods between different neuroimaging modalities (fMRI versus MEG). Compared with the model-free tests used in MEG data, fMRI data are analyzed based on the fixed-effects model (general linear model, GLM), which could increase statistic sensitivity (Monti, 2011).

Study I shed light on the graded nature of motor cortex involvement modulated by abstractness. However, findings from Study II failed to replicate such effect. More studies are needed to validate the effect of abstractness on the involvement of the motor cortex by employing different neuroimaging techniques and comparable experiment paradigms.

# 4.2 The effect of language proficiency on motor cortex involvement

**Study I** and **II** explored the effect of language proficiency on the involvement of the motor cortex. Both studies found greater activation in motor areas for L2 than L1. In addition, Study II further showed that over-activation in the motor area (central sulcus) for L2 in a late stage (600-800 ms) is accompanied by under-activation in the language areas in an early stage (300-500 ms).

Our findings are in accordance with earlier studies showing that the motor system is engaged in both L1 and L2 processing (Birba et al., 2020; De Grauwe et al., 2014; Monaco et al., 2021; Vukovic & Shtyrov, 2014; Zhang et al., 2020).

The greater involvement of the motor system in L2 processing necessitates speculation on the role of the motor system in language processing from a more general perspective. Our findings are in line with an earlier study in showing greater activation in the motor cortex for L2 than L1 (Monaco et al., 2021), despite the variation of latency (275 ms after stimulus-onset in Monaco et al.'s study, 600 ms after stimulus-onset in Study II). The earlier activation in the motor cortex in Monaco et al.'s study may be due to the property of stimuli (single verbs in Monaco et al.'s study vs. verb phrases in Study II) and demand of experiment task (explicit motor simulation in Monaco et al.'s study vs. no demand for explicit motor simulation in Study II). Although specific neural mechanisms underlying L1 and L2 processing might be different between the two studies, both studies demonstrated greater motor cortex involvement for L2 relative to L1.

Nevertheless, the findings of Study I and II are inconsistent with the results of Vukovic and Shtyrov's (2014) study. In Vukovic and Shtyrov's study, L1 involved a greater extent of the motor cortex than L2, manifested as stronger murhythm ERD (event-related desynchronization). The opposite pattern (relative to Study I and II) could be partially ascribed to the difference in brain activation measures.

Based on the findings of Study I and II, we tentatively propose that the greater activation in the motor cortex in L2 may not reflect mental simulation of motoric meaning and thus may not necessarily reflect a higher degree of embodiment. As shown in Study I, greater activation for L2 than L1 is not exclusively observed for the literal and metaphorical language but also for abstract language where no action-related words are embedded. This indicates that motor system involvement is ubiquitous in language processing regardless of its abstractness property. More importantly, Study II showed that greater activation in motor areas in L2 in the late stage is accompanied by underactivation of language areas in the early stage. This might indicate that the motor system is over-recruited to compensate for the insufficient involvement of the language network.

Based on the above, we propose that the greater motor responses in L2 may reflect domain-general functions of the motor system (including memory retrieval, information integration, execution control, etc.) in processing a less proficient and automatized language (Francis, 2005; Miller, 2000; Ullman, 2004; Willems et al., 2010).

# 4.3 Dual-functional role of the motor cortex in semantic processing: an alternative hypothesis

In **Study I** and **II**, motor activation was found across literal, metaphorical, and abstract language. In addition, both studies revealed greater activation in the motor areas for L2 than L1. These findings invite the consideration of an alternative interpretation of motor cortex involvement in language processing in addition to its embodied role (i.e., mental simulation of action-related meanings).

Currently, neural activation observed in the motor cortex has been monolithically interpreted as the consequence of using the motor cortex for mentally simulating action-related meanings (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; Pulvermüller et al., 2005; Schaller et al., 2017; Tettamanti et al., 2005). The interpretation has been made mainly based on the well-established fact that the motor cortex is involved in cognitive functions, such as motor execution, motor planning, and motor imagery (Filimon et al., 2007; Hanakawa et al., 2008; Leonardo et al., 1995). Consequently, activation revealed in the motor cortex in the semantic tasks is assumed to indicate the simulation of action-related meanings. However, as has been highlighted, the engagement of a particular cognitive function cannot be inferred from the occurrence of brain activation in a certain region, due to the possibility that a single brain area may play a role in multiple cognitive functions, either as primary or secondary (cf. reverse inference, e.g., Henson, 2006; Mahon & Hickok, 2016; Poldrack, 2006). In addition to its motor-associated functions, the motor cortex has been reported to be engaged in some other cognitive processes in a sub-dominant way, such as (procedural) memory retrieval, cognitive control, inhibition, and integration (Francis, 2005; Miller, 2000; Mofrad et al., 2020; Ralph et al., 2017; Ullman, 2004; Willems et al., 2010). In the context of language processing, the involvement of the motor cortex could be associated with other cognitive functions in addition to specific linguistic processing, suggested by an absence of language-motor coupling for both lesion and healthy groups during an action-verb generation task (Maieron et al., 2013).

In light of reasonings above, we assume that the greater activation in the motor area in L2 may not indicate a higher level of embodiment in semantic processing but higher demand for cognitive resources to compensate for the lower proficiency and weaker semantic representation of L2 (relative to L1). The interpretation is made based on the activation pattern of language and motor areas in L2 processing (relative to L1), manifested as underactivation of language areas (short insular gyri and planum polare of superior temporal gyrus) at the early semantic processing stage and overactivation of the motor area (central sulcus) at the late semantic processing stage.

Studies of individuals with motor dysfunction (e.g., Parkinson's disease, Huntington's disease, and cerebral palsy) also support the alternative interpretation of motor cortex involvement in language processing (Birba et al., 2017; Buccino et al., 2018; Cardona et al., 2014). In these studies, motor-impaired participants were found to be more impaired for action-related verbs than abstract verbs, which can be explained by participants' incompetence in performing motor-related mental simulation. Nevertheless, it has been neglected that the overall language performance of motor-impaired participants was poorer than that of healthy participants, regardless of the language property (action-related or not). These findings suggest that the impairment of the motor system undermines the processing of not only action-related language but language in general.

Based on the above findings, this dissertation proposed the assumption of the dual-functional role of the motor cortex in language processing. According to the dual-functional assumption, the motor system plays a functional role in both mental simulation and domain-general process in language understanding (e.g., memory retrieval, information integration, etc.). In short, the motor system may play a more diverse role in language comprehension than motor simulation.

The role of the motor system in language processing needs to be further examined with comparable approaches, as data obtained from different neuroimaging modalities or even different measures within the same modality may suggest divergent results. In addition, it is also important to acknowledge the time-varying nature of motor cortex involvement in interpreting the role of the motor cortex, as the motor cortex may play different roles at different stages of language processing.

## 4.4 Spatiotemporal dynamics of abstract concept processing

So far, few studies have examined the involvement of motor areas in abstract concept processing, due to its lack of physical referent and low imageability. By using spatiotemporally sensitive MEG recordings, we investigated to what extent language and motor areas are engaged in processing concepts with different levels of abstractness, i.e., abstract, metaphorical, and concrete concepts. Compared with concrete and metaphorical ones, abstract concepts showed weaker activation in the left posterior part of superior temporal sulcus (STS) at 200-300 ms and stronger activation in the left anterior temporal pole (TP) at 300-400 ms. Results did not reveal any significant differences in the involvement of motor ROIs among abstract, metaphorical, and concrete concepts.

Similar results have been reported in a recent study by Zhang et al. (2022), where the posterior part of left lateral occipital-temporal cortex (LOTC) (similar area to the posterior STS area in our study) was more involved in comprehending action-related concepts (e.g., leap, jump) rather than static concepts (e.g., consider, analyze), due to its stronger connectivity to the visual network. Concrete concepts, which are more directly associated with visual features of concepts, are more likely to elicit neural activities related to mental images compared with abstract concepts. The findings by Zhang et al. implicated a potential role of the LOTC in the representation of action-related concepts, in addition to the sensorimotor cortex proposed by the embodied semantics. Our study for the first time showed different activation patterns in the posterior STS in understanding concrete, metaphorical, and abstract concepts. The temporal difference might indicate a distinctive representation and retrieval of abstract concepts.

Contrary to the posterior STS, we found that activation in the left anterior temporal pole was most robust for abstract phrases around 350-400 ms and attenuated for metaphorical and concrete ones. This finding corroborated with previous studies showing stronger engagement of the anterior temporal pole in processing abstract concepts than concrete ones (Desai et al., 2013; Hoffman et al., 2015; Noppeney & Price, 2004; Pobric et al., 2009). In our study, the greater activation evoked by abstract concepts in the temporal pole might be the result of a higher demand for the semantic integration, considering that abstract concepts usually have a more pronounced linguistic component than concrete concepts (Borghi et al., 2017). These findings suggested an important role of the temporal pole in abstract concept processing. The findings are compatible with the idea of the ATL-hub hypothesis, which proposed that the ATL (anterior temporal lobe) serves as a semantic hub that integrates multi-modal concepts (i.e., multisensory-related concepts) distributed in the domain-specific brain regions view (Lambon Ralph et al., 2017; Patterson & Lambon Ralph, 2016; Patterson et al., 2007; Rogers et al., 2004).

Concepts are represented in a distributed network, with varying emphasis on each subregion of the network depending on the level of abstractness. Recent neuroimaging studies concerning neural underpinnings of concrete and abstract concepts prompt us to reflect on the widely used definition of concrete and abstract concepts, by considering the inter-dependency nature between abstract and concrete concepts (Barsalou et al., 2018). The novel perspective and reflections on the definition of concepts would shed light on future studies exploring neural representations of concrete and abstract concepts.

### 4.5 General discussion

This dissertation consists of three studies exploring the interplay between the language and motor networks in processing native and second language (TABLE 5). Specifically, **Study I**, by using spatially sensitive fMRI recordings, explored the graded nature of motor cortex involvement in language processing modulated by language proficiency (native language and second language) and linguistic abstractness (literal, metaphorical, and abstract). By using temporally sensitive MEG recordings, **Study II** investigated the time-varying interplay between motor and language areas in language processing modulated by language and motor regions are engaged in abstract concept processing (relative to concrete concepts). Overall, the dissertation shows that the involvement of the motor cortex varies with the degree of linguistic abstractness (Study I) and language proficiency (Study I and II). Furthermore, the dissertation shows that processing abstract concepts engages a distinctive spatio-temporal trajectory, compared to concrete concepts (Study III).

The effect of abstractness on the involvement of the motor cortex was found in Study I, manifested as attenuated motor activation from literal to metaphorical to abstract language in both L1 and L2. The findings shed light on the graded nature of motor cortex involvement in language processing, which has not been carefully scrutinized in previous studies. Instead of simply answering YES or NO to the question of whether the motor system is engaged in language processing or not, the study attempted to answer MORE or LESS to the question: to what extent is the motor system engaged in different linguistic circumstances? However, the effect of abstractness was not replicated in Study II. The unreproducibility of results might be due to the sensitivity of analysis methods between different neuroimaging modalities. fMRI data in Study I are analyzed based on the general linear model (GLM), which is a fixed-effects model used to detect task-modulated brain activation by calculating the correlation between the fMRI time-series and the reference model (Monti, 2011). The fixed-effects model may increase statistic sensitivity compared to the model-free, nonparametric permutation tests used in MEG data analyses. In addition, the difference of experiment tasks (Study I: silent reading task; Study II: semantic judgment task) may also have an effect on the inconsistent results between the two studies.

The effect of language proficiency was found in both Study I and II, manifested as overall greater activation in the motor areas for L2 than L1. Study II further showed temporal dynamics of language and motor areas involvement, manifested as overall greater involvement of language areas for L1 (relative to L2) in an early stage and overall greater involvement of motor areas for L2 (relative to L1) in a late stage. We interpreted the over-recruitment of the motor areas in L2 processing as higher demand for cognitive resources to compensate for the inadequate engagement of the language network, i.e., a compensatory role of the motor cortex in L2 understanding. So far, neural activation in motor areas has been mostly interpreted as the result of mentally simulating action-related meanings, as the motor cortex has been known to be involved in a series of motorrelated cognitive processes, such as motor execution, motor planning, and motor imagery (Filimon et al., 2007; Hanakawa et al., 2008; Leonardo et al., 1995). Consequently, activation in the motor cortex revealed in language tasks was interpreted as motor-related responses, i.e., mental simulation of action-related meanings. The reverse inference can be problematic, as there is no one-to-one correspondence relationship between brain regions and cognitive functions (Henson, 2006; Mahon & Hickok, 2016; Poldrack, 2006). In language processing, the motor cortex has also been reported to be engaged in other cognitive functions in a less dominant way, such as memory retrieval, cognitive control, inhibition, and integration (Francis, 2005; Miller, 2000; Mofrad et al., 2020; Ralph et al., 2017; Ullman, 2004; Willems et al., 2010).

Based on the above reasoning, the findings of greater activation in the motor cortex were interpreted as higher demand for cognitive resources to compensate for the weaker semantic representation of a less proficient (or less automatic) language, i.e., L2. Furthermore, the dissertation proposed the assumption of the dual-functional role of the motor system in semantic processing. According to the dual-functional assumption, the motor system plays two functional roles in language processing: 1) In the context of a proficient language (L1), the motor system is more prone to play a role in mentally simulating action-related meanings; 2) In the context of a late-acquired and less proficient language (L2), the motor system is more prone to play a domain-general function, e.g., memory retrieval, information integration, inhibition, etc. Future studies are needed to test and extend the assumption of the dual-functional and compensatory role of the motor system in language processing.

The dissertation also investigated the extent to which language and motor areas are involved in abstract concept processing in the native language, relative to concrete and metaphorical concepts (**Study III**). Results showed that processing concrete concepts (relative to abstract ones) engages the posterior STS to a greater extent in an earlier time window, while processing abstract concepts (relative to concrete ones) relies more strongly on the anterior temporal pole in a later time window. Results implied an essential role of the anterior temporal pole in abstract concept processing. The temporal dynamics of sub-regions in the language network prompt us to reflect on the current demarcation of abstract and concrete concepts, which is made based on whether a concept is associated with a perceivable referent in the physical world. However, as has been emphasized recently, there is no clear cutoff between concrete and abstract concepts (Binder, 2016), and the inter-dependency nature between concepts needs to be considered (Barsalou et al., 2018;). The novel perspective on the definition of concepts is insightful for future studies exploring neural underpinnings of abstract and concrete concept processing.

The findings of this dissertation advance our understanding of how the motor cortex contributes to language processing in general, and specifically, how time-varying interplay between language and motor regions supports native and second language processing. In addition, the dissertation proposes the hypothesis of the dual-functional role of the motor system in language processing, which opens the discussion for alternative interpretations regarding the role of the motor system in language processing.

## TABLE 5Summary of three studies

Study	Objective	Methods	Main findings	Conclusions
<b>Study I</b> Brain and Language,	To explore gradations of motor cortex involvement modulated by language	Participants: 29 Chinese (L1)-English (L2) speakers;	Hierarchically attenuating motor activation from literal to abstract via	Graded motor involvement modulated by abstractness and
2020	proficiency and linguistic abstractness.	<u>Stimuli</u> : 40 literal, 40 metaphorical and 40 abstract verb phrases in both L1 & L2;	metaphorical in both L1 and L2;	language proficiency;
		Tasks: Silent reading & motor localizer tasks:	Overall greater	Dual-functional role of the motor cortex in
			activation in motor areas	semantic processing.
		<u>Data</u> : fiviki recording; ROI-based analysis.	for L2 than L1.	
<b>Study II</b> Neurobiology	To investigate temporal dynamics of involvement	Participants: 26 CHN-ENG speakers;	Greater activation in language ROIs for L1 than	Compensatory role of the motor cortex in L2
of Language, 2023	of language and motor regions during L1 and L2	Stimuli: 60 verb phrases for each condition (literal, metaphorical, and abstract) in both	L2 in an earlier time- window (300-500 ms), and	semantic processing.
	semantic processing.		ROIs for L2 than L1 in a	
		<u>Tasks</u> : Semantic congruency judgment task;	later time-window (600-800 ms);	
		<u>Data</u> : MEG recording; ROI-based analysis.	No effect of abstractness.	
Study III submitted,	To investigate spatiotemporal dynamics of	Participants: S/A;	Delayed activation in pSTS at 200-300 ms, and greater	Distinctive neural underpinnings of
2023	abstract concept processing.	Stimuli: 60 verb phrases for each condition (concrete, metaphorical, and abstract) in L1:	activation in aTP at 300-400 ms for abstract phrases, in	abstract and concrete
			relative to concrete and	revealed by their
		<u>1asks</u> : 5/ A;	metaphorical ones;	spatiotemporal dynamics.
		Data: S/A.	No effect of abstractness on motor ROIs.	

## 4.6 Limitations and future directions

This dissertation has the following limitations. Firstly, a more fine-tuned method can be used in defining the size of regions of interest (ROIs). In the three studies, the size of ROIs is determined by the partition of brain regions in the atlas. However, the atlas-derived ROIs may not fully cover cortical areas with activation and sometimes may include areas where no clear activation appears. In future studies, more customized methods could be used to determine the size of ROIs, e.g., FWHM (full width at half maximum) of peak activation (Hultén et al., 2019; Mollo et al., 2016). Secondly, due to the lack of individual MRI images, surface reconstruction and volumetric segmentation of MEG data were performed based on the template (CN200, Yang et al., 2020). The absence of individual MRI images would compromise the precision of source estimation results. Thirdly, only ROI-based analyses were performed across the three studies, based on the priori hypotheses of language and motor areas. However, whole-brain analyses could also be performed, as it provides a panorama view of the activation pattern in the whole brain, which may shed light on the ROIbased findings. Lastly, this dissertation lacks proper mapping between behavioral and neuroimaging data, which may compromise the interpretation of the neuroimaging data and the understanding of the brain-behavioral relationship (Hauk & Tschentscher, 2013; Krakauer et al., 2017).

Future studies are needed to replicate the findings of the dissertation by employing comparable experiment settings, including demand of experiment task (implicit vs. explicit motor association), properties of stimuli (word vs. phrase vs. sentence), and ways of presentation (word-by-word vs. whole phrase/sentence; visual presentation vs. auditory presentation). As has been pointed out, the recruitment of the motor system in action-related language processing is task-dependent (Giacobbe et al., 2022; Ostarek & Huettig, 2019; Tomasino et al., 2008) and context-dependent (Raposo et al., 2009). In addition, future studies could also explore dynamic functional connectivities between language and motor networks, which would deepen our understanding of how language and motor network coordinates in a time-varying way to achieve language understanding in L1 and L2. Furthermore, future studies could also explore language-motor interplay among neurodivergent groups characterized with language or motor difficulties, which may contribute to the multidimensional understanding of the functional role of the motor cortex in language understanding.

## YHTEENVETO (SUMMARY)

#### Kielellisen ja motorisen järjestelmän orkestrointi kielen ymmärtämisessä: neurokuvantamisen tutkimukset

Tämä väitöskirja koostuu kolmesta tutkimuksesta, joissa tarkastellaan kielellisten ja motoristen aivotoimintojen roolia äidinkielen ja toisen kielen käsittelyssä. Tutkimuksessa I käytettiin aktivaation paikantamisessa tarkkaa fMRI-menetelmää, ja selvitettiin motorisen aivokuoren roolia ja osallistumista kielen prosessointiin. Kielen käsittelyn vaatimuksia manipuloitiin kielellisen taidon (äidinkieli ja toinen kieli) sekä kielellinen abstraktiuden (kirjaimellinen, metaforinen ja abstrakti) osalta. Tutkimuksessa II käytettiin aktivaation ajoituksen suhteen tarkkaa MEG-mentelmää, ja siinä selvitettiin motoristen ja kielellisten alueiden aktivaation ajoituksien eroavuuksia kielen käsittelyn aikana. Samoin kuin tutkimuksessa 1, kielen käsittelyä manipuloitiin kielellisen kompetenssin ja abstraktiustason osalta. Lisäksi tutkimuksessa III selvitettiin, missä määrin kielelliset ja motoriset alueet osallistuvat abstraktien käsitteiden käsittelyyn (suhteessa konkreettisiin käsitteisiin). Kaiken kaikkiaan väitöskirjan tulokset osoittavat, että motorisen aivokuoren osallistuminen vaihtelee kielellisen abstraktisuuden (tutkimus I) ja kielitaidon (tutkimus I ja II) mukaan. Lisäksi väitöskirjassa osoitetaan, että abstraktien käsitteiden käsittelyyn liittyy erilainen aivotoiminnan aktivaatioketju verrattuna konkreettisiin käsitteisiin (tutkimus III).

Tutkimuksessa I havaittiin, että kielen abstraktisuuden taso vaikuttaa motorisen aivokuoren aktivoitumiseen. Motorisen aivokuoren aktivaatio väheni hierarkkisesti, kun siirryttiin konkreettisesta kielestä metaforiseen ja edelleen abstraktiin kieleen, samalla tavoin sekä L1- että L2-kielessä. Tulokset antavat viitteitä motorisen aivokuoren porrastetusta osallistumisesta kielen käsittelyyn, mikä on uudenlainen tarkastelutapa tutkimuksessa. Tässä tutkimuksessa lähestyttiin motorisen järjestelmän roolia asteittaisena, sen sijaan, että olisi pyritty vastaamaan kategorisesti KYLLÄ vs. EI siihen, osallistuuko motorinen järjestelmä kielen prosessointiin vai ei. Toisin sanoen, pyrittiin selvittämään missä määrin eri tekijät vaikuttavat motorisen järjestelmän rooliin kielen käsittelyssä. Abstraktisuuden vaikutusta ei havaittu tutkimuksessa II. Tämä saattaa johtua käytettyjen aivokuvantamismenetelmien sekä analyysimenetelmien eroista. fRMI:llä mitatut aivojen verenvirtaukseen perustuvat tulokset tutkimuksessa I analysoitiin yleistetyllä lineaarisella mallilla (general linear model, GLM) jota käytetään selvittämään tehtävään liittyvän aivoaktivaatiota laskemalla korrelaatio fMRI-aktivaation aikasarjan ja mallissa määritellyn referenssi-aikasarjan välillä (Monti, 2011). Kiinteiden vaikutusten malli voi lisätä tilastollista herkkyyttä verrattuna MEGaineiston analyyseissä käytettyihin mallittomiin, ei-parametrisiin permutaatiotesteihin. Lisäksi koetehtävien erilaisuus (tutkimus I: hiljainen lukutehtävä; tutkimus II: merkitysten arviointitehtävä) voi myös selittää erilaiset tulokset näiden kahden tutkimuksen välillä.

Sekä **tutkimuksessa I** että **II** havaittiin kielitaidon vaikutus, joka ilmeni yleisesti suurempana motoristen alueiden aktivoitumisena L2- kuin L1- kielessä.

Tutkimus II osoitti lisäksi kielellisten ja motoristen alueiden osallistumisen ajallisen suhteen. Kielellisten alueiden aktiivisuus oli suurempi L1-kielen käsittelyn aikana (suhteessa L2 kieleen) aktivaatioketjun varhaisessa vaiheessa ja motoristen alueiden aktiivisuus oli suurempi L2-kielen osalta (suhteessa L1-kieleen) aktivaatioketjun myöhäisessä vaiheessa. Tulkitsimme motoristen alueiden voimakkaamman osallistumisen L2-kielen käsittelyyn johtuvan suuremmasta vaatimuksesta kognitiivisten resurssien käyttöön. Tämä voi kompensoida kielellisten alueiden riittämätöntä aktivaatiota, eli motorisella aivokuorella on kompensatorinen rooli L2-kielen ymmärtämisessä. Motoristen alueiden aktivaatio on useimmiten tulkittu johtuvan kielen merkitysten mentaalisesta simuloinnista. Tulkinta perustuu siihen, että motorisen aivokuoren tiedetään osallistuvan useisiin motorisen kognition prosesseihin, kuten liikkeiden tuottoon, liikkeiden suunnitteluun ja liikkeiden kuvitteluun (Filimon ym., 2007; Hanakawa ym., 2008; Leonardo ym., 1995). Näin ollen kielellisissä tehtävissä havaittu aktivoituminen motorisella aivokuorella tulkitaan motorisiin reaktioihin liittyväksi, eli kielen toimintaa kuvaavien merkitysten mentaaliseksi simuloinniksi. Tällianen käänteinen päätelmä voi olla kuitenkin ongelmallinen, sillä aivojen alueiden ja kognitiivisten toimintojen välillä ei ole yksi-yhteen vastaavuussuhdetta (Henson, 2006; Mahon & Hickok, 2016; Poldrack, 2006). Kielen prosessoinnissa motorisen aivokuoren on osoitettu osallistuvan myös muihin kognitiivisiin toimintoihin, kuten muistinvaraisen tiedon hakuun, kognitiiviseen kontrolliin, inhibitioon ja integraatioon (Francis, 2005; Miller, 2000; Mofrad ym., 2020; Ralph ym., 2017; Ullman, 2004; Willems ym., 2010).

Edellä esitetyn perusteella motorisen aivokuoren voimakkaampi aktivaatio tulkittiin tässä tutkimuksessa suuremmaksi tarpeeksi kognitiivisiin resursseihin, jolla kompensoidaan heikommin hallitun (tai vähemmän automaattisen) kielen eli L2-kielen heikompia semanttista edustuksia. Lisäksi väitöskirjassa esitetään ajatus motorisen järjestelmän kahtalaisesta roolista semanttisessa prosessoinnissa. Tämän oletuksen mukaan motorisella järjestelmällä on kaksi toiminnallista roolia kielen prosessoinnissa: 1) Taitavan kielen (L1) yhteydessä motorisen järjestelmän toiminta liittyy merkitysten mentaaliseen simulointiin, 2) Myöhään omaksutun ja vähemmän taitavan kielen (L2) yhteydessä motorisella järjestelmällä on rooli yleisessä kognitiivisessa kontrollissa, esim. muistinvaraisessa tiedon haussa, tiedon integroinnissa, inhiboinnissa jne. Lisää tutkimusta tarvitaan testaamaan ja laajentamaan oletusta motorisen järjestelmän kahtalaisesta ja kompensoivasta roolista kielen prosessoinnissa.

Väitöskirjassa tutkittiin myös sitä, missä määrin kielelliset ja motoriset alueet osallistuvat abstraktien käsitteiden käsittelyyn äidinkielessä verrattuna konkreettisiin ja metaforisiin käsitteisiin (**tutkimus III**). Tulokset osoittivat, että konkreettisten käsitteiden käsittely (suhteessa abstrakteihin käsitteisiin) aktivoi taempaa sulcus temporalis superiorin aluetta voimakkaammin aivojen aktivaatioketjun aikaisemmassa vaiheessa, kun taas abstraktien käsitteiden käsittely (suhteessa konkreettisiin käsitteisiin) tukeutuu voimakkaammin ohimolohkon kärkeen (temporal pole) myöhemmässä aikaikkunassa. Tulokset viittaavat siihen, että ohimolohkon kärjellä on tärkeä rooli abstraktien käsitteiden käsittelyssä. Kielellisten alueiden aktivoitumisen ajallinen suhde herättää kysymyksen abstraktien ja konkreettisten käsitteiden erottelusta, joka tehdään sen perusteella, liittyykö käsitteeseen havaittavissa oleva yhteys fyysiseen maailmaa. Viimeaikainen tutkimuskirjallisuus on korostanut, että konkreettisten ja abstraktien käsitteiden välillä ei kuitenkaan ole selkeää rajaa (Binder, 2016), ja käsitteiden välinen riippuvuus on otettava huomioon (Barsalou et al., 2018;). Tämä uudenlainen näkökulma käsitteiden määrittelyyn antaa hyvän pohjan tuleville tutkimuksille abstraktin ja konkreettisen kielen käsittelyn aivoperustasta.

Tämän väitöskirjan havainnot lisäävät ymmärrystämme siitä, miten motorinen aivokuori osallistuu kielen käsittelyyn yleisesti, ja erityisesti miten kielellisten ja motoristen alueiden aktivaation ajallinen dynamiikka tukee äidinkielen ja toisen kielen prosessointia. Lisäksi väitöskirjassa esitetään hypoteesi motorisen järjestelmän kahtalaisesta roolista kielen prosessoinnissa, mikä luo pohjaa keskustelulle vaihtoehtoisista tulkinnoista motorisen järjestelmän roolista kielen prosessoinnissa.

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## **ORIGINAL PAPERS**

Ι

## THE ROLE OF MOTOR SYSTEM IN ACTION-RELATED LANGUAGE COMPREHENSION IN L1 AND L2: AN FMRI STUDY

by

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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-ornone and that the motor system has a dual-functional role.

**Key words:** embodied cognition, gradation, linguistic abstraction, metaphorical language, first/second language, fMRI

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## 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 et al., 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, 2008; Gallese, 2005; Gallese & Lakoff, 2015; Fischer & Zwaan, 2008; Pulvermüller & Fadiga, 2010; see review by Wang et al., 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 & Pulvermüller, 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 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). These studies have reported that processing words related to body motion engages the motor cortex, especially in the case of literal language (e.g. catch the ball). 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 (Cardona et al. 2014; Boulenger et al., 2009; Fernandino et al., 2013; García & Ibáñez, 2014; Desai et al., 2015; Buccino et al., 2018; Birba et al., 2017). 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 hypothesical 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 et al., 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.'s (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 et al., 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; Desai et al., 2010, 2013; Cacciari et al. 2011; Raposo et al. 2009). In Desai et al.'s study (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, 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 et al., 2015; Moreno et al., 2015; Santana & de Vega, 2011; Schaller et al., 2017; Wilson & Gibbs, 2007). Desynchronization of oscillatory activation at specific frequency bands, namely 8-13Hz (alpha rhythm, also referred to as mu rhythm) and 15-30Hz (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 (16-25Hz) 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 et al. 2006; Raposo et al. 2009; Desai et al. 2010, 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 (Francis, 2005; Abutalebia & Green, 2007; 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, 2015; Jarvis & Pavlenko, 2008; Degani et al., 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 et al., 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 actionrelated 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 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 ( $\mathbb{Z}$   $\mathbb{R}$   $\mathbb{R}$ , 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 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.

1			
	LI 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	

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

#### 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 2-8s to allow optimal statistical separation of BOLD responses to each condition (Dale, 1999; Desai et al., 2010). 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 3T 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:  $240 \times 240$ , resolution matrix: $64 \times 64$ , slice thickness: 4mm,

voxel size:  $3.5 \times 3.5 \times 3.5$  mm<sup>3</sup>, flip angle: 90-degree, TR: 2000ms, TE: 30ms. Volumes were composed of 32 axially oriented 4-mm slices with a 1 mm interslice gap. Structural T1-weighted 3D images of the whole brain were obtained with  $1 \times 1 \times 1$  mm<sup>3</sup> 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  $3\times3\times3$  mm<sup>3</sup> resolution, and smoothed with a FWHM 6 mm Gaussian kernel. In the temporal domain, detrend and a band pass filter with 0.01mHz to 150mHz 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 was used for the individual and group level analysis (www.fil.ion.ucl.ac.uk/spm/software/spm12). 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 conditions (literal> analyses between 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 firstlevel 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 et al., 2012; Rapp et al., 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 metaanalysis 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 et al. 2012; McLaren et al. 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. 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 (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.



Figure 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).

	T value	X	у	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

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

(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.)

#### 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 area), and language ROIs BA39 (middle temporal gyrus), BA44 (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 (middle temporal gyrus); (3) metaphorical-abstract contrast showed greater BOLD responses for the metaphorical gyrus) and lower activation in BA21 (middle temporal gyrus); (3) metaphorical-abstract contrast showed greater BOLD responses for the metaphorical gyrus) and lower activation in BA21 (middle temporal gyrus); (3)

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.



Figure 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).
	T value	X	у	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

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

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

## **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).



Figure 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).

	T value	X	у	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	L precentral gyrus		59
	-2.980	48	-75	24	R	R middle temporal gyrus		81
Μ	-4.046	-60	9	33	L	precentral gyrus	BA6	112
	-2.216	-48	-42	9	L	L middle temporal gyrus		54
Α	-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

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

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

## **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 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<a href="mailto:abstract">abstract</a>).

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).



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

	Seed Region	T value	X	у	Z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
	BA45	-3.120	39	-24	63	R	precentral gyrus	BA4	52
L>M		-3.881	-9	-12	57	L	supplementary motor area	BA6	228
	BA6	-3.053	54	-30	-3	R	middle temporal gyrus	BA21	69
	BA45	-4.969	12	-24	66	R	precentral gyrus	BA4	302
		-4.049	-9	-12	57	L	supplementary motor area	BA6	529
L>A	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	*	*	*	*	*	*	*	*

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

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

## 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 BA4 (precentral gyrus) was greater in the literal-abstract 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 is greater in the literal condition than in the abstract contrast (uncorrected gyrus) was greater in the literal gyrus) was gyrus) was gyrus gyrus) was gyrus gyr

condition. For the metaphorical-abstract contrast (uncorrected, p < 0.05), the connectivity between seed region BA45 frontal (inferior 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 the L2 Experiment showed a of hierarchically increasing strength of functional connectivity across the three conditions (literal>metaphorical>abstract).



Figure 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 ( $p \le 0.05$ , voxel size>20)

	Seed Region	T value	X	у	Z	Hem	Anatomical regions (AAL)	Brodmann	Number of voxel
	BA45	2.633	-39	-21	69	L	precentral gyrus	BA4	61
L>M		-2.414	-9	-9	72	2 L supplementary motor		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
	BA45	3.286	-3	-21	54	L	supplementary motor area	BA4	67
M>A		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.)

## 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 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; Citron et al., 2014; Desai et al., 2010, 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  $\ddagger$  in the written form to indicate that the meaning of the character is associated with hand or arm movement (*e.g.*  $\frac{1}{M}/\frac{1}{grasp}$ ,  $\frac{1}{W}/\frac{1}{hrow}$ ,  $\frac{1}{W}/\frac{1}{wipe}$ ,  $\frac{1}{W}/\frac{1}{wipe}$ ). 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 abstract meaning, metaphorical phrases and expressions are usually translated into a chunk of abstract translation. Consequently, instead of the 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's (2014) study, was it concluded that the neural representation of L1 is more embodied than L2, as suggested by greater murhythm ERD (less murhythm 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 et al., 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 et al., 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. (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 languagerelated functions, which would include e.g. cognitive control and inhibition, information integration, (procedural) memory retrieval (Francis, 2005; Miller, 2000; Willems et al., 2010; Ullman, 2004). 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).



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

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) (Guan et al., 2013; Dreyera & Pulvermüller, 2018; Vukovic et al., 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 that motor dysfunctions not only influence actionrelated 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.

# **Conflicts of interest**

The authors declare no conflicts of interest.

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# SPATIOTEMPORAL DYNAMICS OF ACTIVATION IN MOTOR AND LANGUAGE AREAS SUGGEST A COMPENSATORY ROLE OF THE MOTOR CORTEX IN SECOND LANGUAGE PROCESSING

by

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### RESEARCH ARTICLE

# Spatiotemporal Dynamics of Activation in Motor and Language Areas Suggest a Compensatory Role of the Motor Cortex in Second Language Processing

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Keywords: motor cortex involvement, magnetoencephalography, native language, second language, language proficiency, abstractness

#### ABSTRACT

The involvement of the motor cortex in language understanding has been intensively discussed in the framework of embodied cognition. Although some studies have provided evidence for the involvement of the motor cortex in different receptive language tasks, the role that it plays in language perception and understanding is still unclear. In the present study, we explored the degree of involvement of language and motor areas in a visually presented sentence comprehension task, modulated by language proficiency (L1: native language, L2: second language) and linguistic abstractness (literal, metaphorical, and abstract). Magnetoencephalography data were recorded from 26 late Chinese learners of English. A cluster-based permutation F test was performed on the amplitude of the source waveform for each motor and language region of interest (ROI). Results showed a significant effect of language proficiency in both language and motor ROIs, manifested as overall greater involvement of language ROIs (short insular gyri and planum polare of the superior temporal gyrus) in the L1 than the L2 during 300-500 ms, and overall greater involvement of motor ROI (central sulcus) in the L2 than the L1 during 600-800 ms. We interpreted the over-recruitment of the motor area in the L2 as a higher demand for cognitive resources to compensate for the inadequate engagement of the language network. In general, our results indicate a compensatory role of the motor cortex in L2 understanding.

#### INTRODUCTION

The engagement of the motor cortex in language processing has been intensively discussed within the framework of embodied cognition. Based on the embodied view, language processing, specifically semantic processing (i.e., processing of meaning), involves not only classic language-related regions but also the motor system to simulate the perceptual meaning conveyed by words (Barsalou et al., 2008; Fischer & Zwaan, 2008; Gallese & Lakoff, 2005;

Pulvermüller & Fadiga, 2010; Zwaan, 2014). The embodied view of semantic processing has been supported by neuroimaging and electrophysiological studies during the past decade, showing neural activations and oscillations in the motor cortex during meaning understanding (Fargier et al., 2012; Fernandino et al., 2013; Klepp et al., 2014, 2015; Mollo et al., 2016; Moreno et al., 2013). In addition, the action-sentence compatibility effect (Glenberg & Kaschak, 2002) has been taken as evidence for the involvement of the motor system in action-related semantic processing. Faster response was found when the direction of movement is congruent with the direction conveyed by the sentence (Glenberg et al., 2008; Kaschak & Borreggine, 2008; Santana & de Vega, 2011; Zwaan & Taylor, 2006). However, some recent studies failed to replicate any such motor compatibility effect (Greco, 2021; Morey et al., 2022; Papesh, 2015).

Clinical studies have provided more direct evidence for the involvement of the motor cortex in semantic processing by investigating patients with motor impairment (e.g., Parkinson's disease, or PD; Buccino et al., 2018; Cardona et al. 2014; Desai et al., 2015; Fernandino et al., 2013; Kargieman et al., 2014; Kemmerer et al., 2012; Monaco et al., 2019). These studies showed that the motor-impaired participants had a selective difficulty in comprehending the action-related words (e.g., kick), manifested as a lower accuracy rate, longer response time, and an absence or attenuation of modulation of motor responses in patients with PD, compared with the healthy control group. The revealed association of impaired motor skills and deficits in understanding action-related meaning would support the embodied account of semantic processing. However, some other lesion studies failed to find the causal effect of motor cortex impairment on the processing of action-related meaning (Maieron et al., 2013; Papeo et al., 2010). These studies showing the dissociation of motor impairment and motoric semantic processing question the necessity of the motor cortex in language processing.

The emerging controversial findings have stirred up critiques and reflections on the embodied assumptions of language processing. As has been pointed out, the rapidly growing popularity of the embodied account is likely to result in the ignorance of other potential interpretations (see, e.g., Chatterjee, 2010; Hauk & Tschentscher, 2013; Mahon, 2015; Mahon & Hickok, 2016). Studies with the embodied hypothetical stance tended to interpret the data within the theoretical framework of embodiment with a prior hypothetical bias. For example, results showing motor activation in language tasks have been monotonically interpreted as the result of mental simulation of motor-related meaning, and therefore taken as an additional piece of evidence to confirm the embodied assumption. However, activation of the motor cortex may not necessarily be due to the mental simulation of motoric meaning. It can be ubiquitous in the language processing in general (Meteyard et al., 2012; Tian et al., 2020) or related to other aspects beyond strict linguistic processing (Maieron et al., 2013).

#### Functional and Epiphenomenal Role

The emerging controversial findings impelled researchers to re-examine the role of the motor cortex in language processing and test whether activations in the motor cortex reflect the retrieval of lexical-semantic information (functional role) or arise as a byproduct of post-semantic motor imagery (epiphenomenal role). Some studies attempted to disentangle the functional and epiphenomenal role by scrutinizing the temporal information of motor activations (García et al., 2019; van Elk et al., 2010). In van Elk et al.'s (2010) study, an early activation of the motor area indexed by the mu rhythm event-related desynchronization (ERD) was found preceding semantic processing (around 400 ms after onset) and sustaining in parallel with semantic processing (around 700 ms after onset). Based on the early latency of motor

activation, it was concluded that motor activation primarily reflected lexical-semantic retrieval and integration rather than post-lexical motor imagery.

Compared with neurotypical studies, lesion (pathological and virtual transient dysfunctions caused by repetitive transcranial magnetic stimulation [rTMS]) studies offered a more direct pathway for scrutinizing the causal role of the motor cortex, since researchers were able to detect the causality by manipulating stimulations over the motor cortex (Bocanegra et al., 2017; Desai et al., 2015; Fernandino et al., 2013; Pulvermüller et al., 2005; Reilly et al., 2019; Vukovic et al., 2017). In Vukovic et al.'s (2017) study, rTMS was employed over the left motor cortex within 200 ms of word onset to examine whether the stimulation would affect the processing of hand-related action words and abstract words in the lexical decision task-which requires very shallow lexical-semantic processing-and semantic judgment task—which requires explicit access to action-related meaning processing. The stimulation impaired the comprehension of the action words but facilitated that of the abstract words, compared with the performance in the lexical decision task. The interruptive effect of stimulation on lexical-semantic processing suggested a functional role of the motor cortex in semantic processing. Consistent results were also reported among studies concerning motor disorders, where associations were found between the impairment in action performance and the impairment in action-verb processing (Bocanegra et al., 2017; Desai et al., 2015; Fernandino et al., 2013).

Conversely, some studies reported dissociations between motor impairment and action semantic deficits (Maieron et al., 2013; Papeo et al., 2010). In Maieron et al.'s (2013) study, functional magnetic resonance imaging (fMRI) was employed to examine functional connectivity between the language network and primary motor cortex (M1) in an action-verb naming task. Participants were patients whose lesions involved (or spared) the M1 and healthy controls. It was found that lesions in the M1 did not degrade the performance of the action-verb naming task compared with the healthy controls. Results of the functional connectivity further revealed a lack of task-modulated connectivity between the M1 and language network in the action-verb naming task for both lesion and healthy groups. These findings indicated an accessory rather than functional role of the motor cortex in the processing of action words.

#### Gradations of Motor Cortex Involvement

Instead of confirming or refuting the embodied hypothesis, some studies turned to explore the degree of motor cortex involvement, such as whether the motor cortex was differentially involved in different language settings. As highlighted by Chatterjee (2010) and Meteyard et al. (2012), the discussion of the graded nature of embodiment would shed light on the role that the motor system plays in semantic processing.

The gradation of motor cortex involvement has been mostly explored from the perspective of language proficiency (L1: native language; L2: second language) (Birba et al., 2020; De Grauwe et al., 2014; Monaco et al., 2021; Tian et al., 2020; Vukovic & Shtyrov, 2014; Zhang et al., 2020). By employing a passive reading task involving action-related words, Vukovic and Shtyrov (2014) found that the engagement of the motor cortex was greater for L1 than L2 for German-English speakers, indexed by a stronger ERD for the L1 than the L2 at around 8–12 Hz (mu rhythm). The stronger ERD for the L1 was interpreted as the result of a more integrated perception-action circuit for the L1 lexical-semantic representation. In contrast, in our earlier fMRI study (Tian et al., 2020), stronger activation of the motor cortex was found for the L2 than the L1, which was interpreted as the consequence of higher demand for cognitive resources as compensation for a less proficient language. Similarly, Monaco et al. (2021) also reported

greater motor excitability for the L2 (English) than the L1 (French) in an action-related semantic judgment task, indexed by a higher motor evoked potentials for the L2 when the TMS was given 275 ms after word onset. However, the authors only claimed a different degree of motor cortex involvement between L1 and L2 semantic processing without further interpreting the implications underlying such differences. On the other hand, a similar degree of motor cortex activation has been reported (De Grauwe et al., 2014) between the L1 (Dutch native speakers) and the L2 (German advanced learners of Dutch) groups in performing a lexical decision task involving cognates and non-cognates with motor or non-motor-related meanings. The study therefore concluded that the lexical-semantic representation of the L2 was adequate to induce a similar degree of motor activation relative to the L1.

In addition to language proficiency, the gradation of motor cortex involvement has also been explored by manipulating the level of linguistic abstractness (e.g., literal/metaphorical/abstract language; Desai et al., 2013; Schaller et al., 2017; Tian et al., 2020). In Desai et al.'s (2013) study, four levels of linguistic abstractness were manipulated at sentence level, including literal action, metaphorical action, idiomatic action, and abstract verb. The blood oxygen level dependent signals of fMRI showed attenuated activation in the motor regions with the increase of linguistic abstractness (literal > metaphor > idiom > abstract). In our earlier study (Tian et al., 2020), we reported a similar decremental trend of motor activation with a hierarchically decreasing pattern of motor cortex activation from the literal to the abstract verb phrases.

#### The Present Study

Previous studies have advanced our understanding of the motor system in semantic processing by exploring the gradations of motor cortex involvement in different linguistic circumstances. However, the discussed studies using fMRI, electroencephalogram (EEG), or TMS lacked either temporal or spatial accuracy in describing brain activation. Combining spatial and temporal resolution is crucial for the comprehensive understanding of how (and when) the motor cortex contributes to language understanding since timing and source dynamics of brain activation needs to be extracted simultaneously from language and motor areas. Majority of previous studies only focused on the motor regions of interest (ROIs), while ignoring the simultaneous neural activities of the language regions. In the present study, we employed magnetoencephalography (MEG) with millisecond temporal resolution and sub-centimeter spatial resolution to explore the temporal activation dynamics of motor and language areas in semantic processing. Specifically, we aim to investigate whether the degree of the engagement of motor and language areas is modulated by language proficiency (native language and second language) and linguistic abstractness (literal, metaphorical, and abstract).

#### METHODS

#### Participants

A total of 26 participants (8 male, 18 female) were recruited from the University of Jyväskylä, Finland. Participants were Chinese-English speakers, who started to learn English at the mean age of 9.77 (SD = 2.73) and had an average of 16.38 years' (SD = 4.67) experience in learning English. Participants had the Lextale vocabulary test (www.lextale.com; Lemhöfer & Broersma, 2012) to measure their L2 vocabulary knowledge (mean  $\pm SD$ : 74.18  $\pm$  8.35). All participants were right-handed with normal or corrected-to-normal vision. None of the participants reported having any history of neurological disorder. Participants gave informed consent prior to participation. Participants were compensated for their participation in the experiment. The study was approved by the ethics committee of the University of Jyväskylä. Two participants

were excluded from data analysis due to the low accuracy rate in behavioral performance (below 75%, mean = 93.04%, SD = 6%), resulting in 24 participants in the final analysis.

#### **Experiment Design**

To examine the effect of language proficiency and linguistic abstractness on the degree of motor cortex involvement, L1 and L2 experiments were designed. Within each experiment, the factor of linguistic abstractness was manipulated with a gradual increase of abstractness from literal to metaphorical to abstract conditions. Each trial consisted of two verb phrases, with the second verb phrase either semantically congruent or incongruent with the first one. Participants were required to perform a semantic judgment task, where they needed to judge whether the second verb phrase shared the same meaning as the first phrase by pressing the response buttons.

#### Stimuli

A total of 180 verb phrases (60 in each condition) were used in both L1 and L2 experiment. The literal and metaphorical phrases contained an action-related verb, either hand or arm related. The abstract phrase connoted the same meaning expressed by the metaphorical one (Table 1). Phrases in the L1 experiment were semantically equivalent to those in the L2 experiment, with few exceptions in the metaphorical condition, due to the lack of Chinese equivalents of some English metaphorical expressions. The verb phrases in both L1 and L2 experiments shared the same syntactic structure: verb + object. A frequency norming test and familiarity rating test were conducted to ensure that stimuli across conditions did not differ significantly in the aspects of word frequency and word familiarity (p > 0.01). Motor-relatedness of all stimuli was evaluated on a 5-point scale (1: not related at all; 5: very related): L1 experiment (literal:  $4.60 \pm 0.40$ ; metaphorical: 2.78  $\pm$  1.24; abstract: 2.12  $\pm$  1.23) and the L2 experiment (literal: 4.39  $\pm$ 0.58; metaphorical: 2.64  $\pm$  0.96; abstract: 2.11  $\pm$  1.04). Only the first verb phrase, which is independent of task-related strategic manipulations, was used for further MEG analysis.

#### **Experimental Procedure**

Т

L1 and L2 experiments shared the same experimental procedure. As suggested by previous studies, L1 could have a stronger translation priming effect on L2 than the other way around (i.e., asymmetrical cross-language priming effects; Chen et al., 2014; Keatley et al., 1994; Smith et al., 2019). To avoid the translation priming effect, L1 experiment was presented after L2 experiment. Trials were shown in a pseudo-randomized order. As shown in Figure 1, each

1	Table 1.         An exemplar of stimuli in the L1 and L2 experiment							
	L1 (Chinese)	L2 (English)						
Literal	<b>抓住胳膊</b> 握住胳膊	seize the arm – hold the arm						
	<b>抓住胳膊</b> 摔伤胳膊	seize the arm – hurt the arm						
Metaphorical	<b>抓住机会</b> –把握机会	seize the chance – grab the chance						
	<b>抓住机会</b> _错过机会	seize the chance – give up the chance						
Abstract	<b>珍惜机会</b> –爱惜机会	cherish the chance – appreciate the chance						

Note. The L1 and L2 stimuli are semantically equivalent.

珍惜机会--放弃机会

cherish the chance - abandon the chance



Figure 1. Schematic view of the experimental procedure.

trial began with a 500 ms fixation at the center of the screen, followed by a 500 ms long blank interval. Afterward, the first verb phrase was presented for a duration of 1,500 ms, followed by a 1,000 ms long blank interval. The second verb phrase was then presented for 1,500 ms, followed by "?" with a duration of maximal 3,000 ms. Participants were expected to give a response after the "?" appeared. Visual stimuli were presented using Presentation software (Neurobehavioral Systems, 2022). L1 stimuli were in KaiTi font and L2 stimuli in Times New Roman font. The viewing distance from participants' eyes to the stimuli on the projection screen was one meter. The L1 stimuli subtended a horizontal visual angle of 3° 5', and the L2 stimuli subtended a horizontal visual angle of 4° 58'.

#### **MEG Data Recording**

Continuous neuromagnetic signals were recorded using a 306-channel (102 magnetometers and 204 planar gradiometers) whole-head MEG system (MEGIN Oy, 2022) in a magnetically shielded room at the Centre for Interdisciplinary Brain Research, University of Jyväskylä, Finland. The head position of each subject was monitored by five head-position indicator (HPI) coils attached over the forehead and behind each ear. Electrooculography signals were recorded simultaneously by four electrodes attached around the eyes: above/below the right eye, near the corner of the left/right eye. One ground electrode was attached to the collar bone. The position of three fiducial landmarks (nasion, left/right preauricular points), as well as approximately 120 digitization points over the scalp, were acquired to establish the head coordinate frame for the coregistration between MEG data and the MRI template. MEG signals were online bandpass filtered at 0.1–330 Hz with a sampling rate of 1000 Hz.

#### MEG Data Preprocessing and Source Estimation

Raw MEG data were processed in MaxFilter 2.2 (Elekta, 2010) with the time-domain extension of the signal space separation method to minimize external magnetic disturbance and withinsensor artifacts and to compensate for head movement (Taulu & Kajola, 2005). Head position was estimated with a buffer length of 30 s and a correlation limit of 0.980. Head movement correction was performed using a 200 ms window with a 10 ms step. The error limit of HPI coil fit acceptance was 5 mm with a g-value of 0.98.

The preprocessing was performed with Meggie, a graphic user interface built in-house based on MNE-Python software (Gramfort et al., 2013). First, visual inspection was done to identify and exclude the bad data segments in the continuous MEG data. Then, MEG data were resampled to 250 Hz. A lowpass filter of 40 Hz (transition bandwidth 0.5 Hz, filter length 10 s) was applied. Physiological artifacts related to heartbeat, blink, and saccade were removed using a semiautomatic independent component analysis method. Event-related epochs were extracted from -200 ms to 1,000 ms relative to the onset of the first verb phrase. A 200 ms interval before the onset was used as the baseline. MEG epochs with an amplitude exceeding 3,000 fT/cm for gradiometers or 4,000 femtoteslas (fT) for magnetometers were rejected from further analysis.

In the calculation of evoked responses for the literal, metaphorical, and abstract conditions, the first verb phrase was combined across the congruent and incongruent trials. Evoked responses were obtained by averaging the signals of each condition (literal, metaphorical, and abstract) in each experiment (L1 and L2 experiment).

Source estimation was performed in MNE-Python (Version 0.17.0; Gramfort et al., 2013). The CN200 template (https://www.nitrc.org/projects/us200\_cn200; Yang et al., 2020), based on T1-weighted magnetic resonance images of 250 healthy Chinese adults, was used for cortical reconstruction and volumetric segmentation. Coregistration between the CN200 template scalp and the digitized scalp was performed for each participant using a three-axis scaling mode. Shrunk covariance with cross-validation was used to estimate the noise-covariance matrix (Engemann & Gramfort, 2015).

Dynamic statistical parametric mapping (dSPM; Dale et al., 2000), which is based on minimum-norm estimate (Hämäläinen & Ilmoniemi, 1994), was used for source estimation with a source space consisting of 4,098 vertices and 4,098 loose-constraint and depth-weighted current dipoles (loose = 0.2, depth = 0.8) distributed on the cortical surface in each hemisphere. Source estimation results were then noise normalized using the dSPM. The source estimates across participants were morphed to the same cortical space (CN200 template).

#### **ROI Selection**

Regions of interest were selected in a hybrid way. First, based on the timing of peak activities in the grand-averaged sensor waveform (Figure 2A), the spatial distribution of cortical sources corresponding to each peak was identified (Figure 2B).

Next, the source distribution was compared against previous meta-analysis results of neuroimaging studies pertaining to semantic processing and motor performance/imagery. Brain regions appearing in both the data-derived cortical activation maps and previous meta-analyses were selected as ROIs for the present study. The selection was done by using MNE\_analyze (https://mne.tools/0.17/manual/gui/analyze.html#the-labels-menu; Gramfort et al., 2014). First, label names corresponding to the literature-derived brain regions were selected from the parcellation list (Destrieux Atlas a2009s; Destrieux et al., 2010). Then, the partition of the selected region was overlaid with the MEG data on the inflated cortical surface. Only areas which showed prominent activation within the partitions were selected as ROIs. Both language and motor ROIs were selected left-lateralized due to only minor activation in the right hemisphere (Figure 2B). All ROIs were parcellated based on the Destrieux Atlas a2009s (Destrieux et al., 2010; see the schematic view of ROIs in Figure 3).

The above procedure resulted in the following language ROIs: short insular gyri (partially overlapping with inferior frontal gyrus; Binder et al., 2009; Friederici et al., 2003; Rueckl et al., 2015), planum polare of the superior temporal gyrus (part of anterior temporal cortex;



**Figure 2.** Grand-averaged results at sensor and source level. (A) Grand-averaged sensor waveform (204 gradiometers) across conditions in the L1 and L2 experiments; the light-shaded areas indicate the time window applied to the region-of-interest-based statistical analysis. (B) Grand-averaged source activation quantified as mean dynamic statistical parametric mapping (dSPM) value over time points corresponding to each peak: ±40 ms duration prior and after the relatively transient peaks (peak 1 and peak 2), and ±100 ms prior and after the relatively sustainable peaks (peak 3 and peak 4). The intensity of the color in the cortical activation map indicates the degree of dSPM value. L1: native language (Chinese); L2: second language (English); lit: literal; met: metaphorical; abs: abstract; L: left hemisphere; R: right hemisphere.

![](_page_95_Figure_1.jpeg)

**Figure 3.** Grand-averaged source time courses for the literal, metaphorical, and abstract conditions in the L1 and L2 experiments in the indicated ROIs (language ROIs: short insular gyri, planum polare of the superior temporal gyrus, and superior temporal sulcus; motor ROIs: inferior part of the precentral sulcus and central sulcus). The parcellation of each ROI is shown in the inflated brain surface with a lateral view. For a better view, the planum polare of the superior temporal gyrus is also shown with a rostral view.

Carreiras et al., 2013; Lambon Ralph et al., 2017; Patterson et al., 2007), and superior temporal sulcus (Citron et al., 2020; Rueckl et al., 2015). Motor ROIs were selected as the inferior part of precentral sulcus and central sulcus (part of primary motor cortex; Hari et al., 1998; Hétu et al., 2013; Michelon et al., 2006; Porro et al., 1996; Yousry et al., 1997). The ROI-based source time courses are shown in Figure 3.

#### **Time Window Selection**

The time window was selected based on the latency of peak activities in the grand-averaged sensor waveform (Figure 2A) and the corresponding time-resolved source activation maps (Figure 2B). Based on the visual inspection, four peaks were identified in the sensor waveform: peak 1 at around 140 ms, peak 2 at 260 ms, peak 3 at 400 ms, and peak 4 at 700 ms.

Based on the source activation map, the first two peaks reflected activation in the visual cortex (peak 1) and more distributed areas across occipital-temporal lobes (peak 2), which were not included for statistical analysis. During peak 3 (300–500 ms, with peak activity at around 400 ms) and peak 4 (600–800 ms, with peak activity at around 700 ms), activation was found within temporal and frontal-central lobes, overlapping with our selected ROIs. Therefore, these two time windows, TW1 (300–500 ms) and TW2 (600–800 ms), were used for further statistical analysis.

#### Statistical Analysis

Statistical analysis was performed on the amplitude of the source waveform (represented as dSPM value) extracted from each ROI separately for TW1 and TW2. To examine the effect of language proficiency and linguistic abstractness, the nonparametric two-way repeated measures

12023

analysis of variance with spatiotemporal clustering was performed in MNE-Python. To solve the multiple comparison problem, a cluster-based permutation test across time and space was employed (Maris & Oostenveld, 2007). The randomization times of the permutation test were 1,000, with a threshold for cluster inclusion  $\alpha = 0.05$  and the permutation significance  $\alpha = 0.05$ . The *p*-values across language ROIs and motor ROIs were corrected for multiple comparison using Benjamini-Hochberg false discovery rate (FDR; Benjamini & Hochberg, 1995).

#### RESULTS

#### **Behavioral Results**

We estimated the behavioral competence in L1 and L2 by analyzing the behavioral performance in the semantic judgment task. There was no significant difference between the L1 and L2 in the reaction time (p > 0.05, L1 (mean, *SD*): 587.12 ms ± 62.14, L2: 626.20 ms ± 71.59), but the accuracy rate was higher in L1 (96.25% ± 1.8%) than in L2 (91.94% ± 3.9%) (p < 0.001).

#### General Pattern and Time Course of Activation

The rough level activation timing (grand-averaged sensor waveform across the 204 gradiometers) and spatial distribution (source activation within the major activation peaks) across conditions in the L1 and L2 experiments are shown in Figure 2A and 2B. The source activation map revealed robust activation in the occipital lobe at 130 ms for both the L1 and L2, with slightly greater amplitude for the L1 than the L2. At around 260 ms, activation was found in the posterior temporal area for the L1 and in the lateral occipital-temporal area for the L2. At the peak around 400 ms, a notably greater amplitude was observed for the L1 than the L2. Activation in L1 was broadly distributed to the insular area (partially overlapping with the inferior frontal gyrus), posterior temporal area, anterior temporal area, inferior part of precentral area and central area. For the L2 (mainly the metaphorical condition), robust activation was observed mainly in the posterior temporal area. At around 700 ms, the pattern between L1 and L2 was reversed: L2 showed greater amplitude than L1 in the central and precentral areas.

Table 2.	Statistical	results of	region-of-inter	est (ROI) ar	nalyses on	source data
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					<i>p</i> -values (FDR-corrected)					
	Parcellation (Destrieux	Terminologia		3	00–500 m	is	600–800 ms			
	Atlas a2009s) <sup>a</sup>	Anatomica <sup>b</sup>	#Vertice	A:B	А	В	A:B	А	В	
Language ROIs	G_insular_short	Short insular gyri	732	0.095	0.042*	0.258	0.243	0.970	0.240	
	G_temp_sup-Plan_polar	Planum polare of the superior temporal gyrus	876	0.215	0.042*	0.258	0.406	0.613	0.290	
	S_temporal_sup	Superior temporal sulcus	5216	0.095	0.326	0.271	0.298	0.842	0.451	
Motor ROIs	S_precentral-inf-part	Inferior part of the precentral sulcus	1587	0.056	0.466	0.859	0.465	0.056	0.246	
	S_central	Central sulcus	3139	0.073	0.515	0.512	0.465	0.020*	0.246	

Note. A:B: interactions between language proficiency and linguistic abstractness; A: the main effect of language proficiency; B: the main effect of linguistic abstractness. The anatomical parcellation was based on Destrieux Atlas a2009s. Statistical significance (p < 0.05) is marked in bold with an asterisk.

<sup>a</sup> Destrieux et al. (2010).

<sup>b</sup> FIPAT (2019).

![](_page_97_Figure_1.jpeg)

Language ROIs

![](_page_97_Figure_3.jpeg)

Motor ROIs

![](_page_97_Figure_5.jpeg)

Figure 4. Results of permutation F test on the language and motor ROIs. (Left) Significant clusters at source space (clusters exceeding the randomization distribution under H0 hypothesis). The intensity of the color in the cortical map indicates the duration of the time window of clusters. (Right) Source time courses (represented as dSPM value) extracted from significant spatiotemporal clusters; light orange shading area shows time window of the significant cluster. dSPM: dynamic statistical parametric mapping.

#### Statistical Results

Cluster-based permutation F test on source data was performed for each language and motor ROI in the TW1 (300–500 ms) and TW2 (600–800 ms) respectively. Statistical results are shown in Table 2. Language and motor ROIs with significant spatiotemporal clusters are shown in Figure 4.

For the language ROIs, in the TW1, the cluster-based permutation *F* test revealed a significant main effect of language proficiency in the short insular gyri (p = 0.042) and the planum polare of the superior temporal gyrus (p = 0.042), manifested as greater activation within these areas for the L1 than for the L2. Statistical analysis did not reveal any significant interaction effect or the main effect of abstractness. In the TW2, no significant effect was found for language ROIs.

For the motor ROIs, no significant effect was found in the TW1. In the TW2, results showed a significant main effect of language proficiency in the central sulcus (p = 0.020), manifested as greater activation in the L2 than in the L1. No significant interaction effect or the main effect of abstractness was found.

#### DISCUSSION

In this MEG study, we investigated the degree of involvement of the language and motor areas in a language comprehension task. We employed spatiotemporally sensitive MEG recordings, which allowed us to examine the temporal trajectory of language and motor cortex activation. Specifically, we investigated whether the degree of involvement of language and motor areas in the stage of semantic processing was modulated by learner-specific factors (i.e., language proficiency), and/or by stimulus-specific factors (i.e., level of abstractness of the language stimuli).

Our source analysis evidenced a typical spatiotemporal trajectory of visual word processing, which witnessed an early robust activation in the occipital area, followed by activation flowing from the posterior to the anterior temporal and frontal areas (Brennan & Pylkkänen, 2012; Carreiras et al., 2013). In addition, the source estimation results showed neural activation of motor areas across all conditions (literal, metaphorical, and abstract) in both native language (L1) and second language (L2). More importantly, our results showed an overall greater involvement of language areas (short insular gyri and planum polare of the superior temporal gyrus) in the L1 than in the L2 in the time window of 300–500 ms, which has been broadly associated with semantic analysis (Kutas & Federmeier, 2011; Lau et al., 2008; Lau et al., 2013). Although greater activation in the posterior superior temporal sulcus can be seen for the L1 than the L2 in the grand-averaged source results (Figure 2B), it failed to show any statistically significant difference. In addition, our results showed an overall greater involvement of motor area (central sulcus) in the L2 than in the L1 in the late time window of 600– 800 ms, which might be associated with post-semantic analysis and integration.

#### Compensatory Role of the Motor Cortex in Late-Acquired L2 Processing

Our findings corroborate previous studies in showing that the motor cortex is involved in the processing of not only the L1 but also the L2 (Birba et al., 2020; De Grauwe et al., 2014; Monaco et al., 2021; Tian et al., 2020; Vukovic & Shtyrov, 2014; Zhang et al., 2020). In fact, our results suggest a stronger role for motor areas in the L2 than the L1. Our findings are also in line with earlier studies which suggested that the motor (or sensorimotor) area is involved in the processing of not only action-related but also abstract meaning (Dreyer & Pulvermüller,

2018; Guan et al., 2013; Tian et al., 2020; Vukovic et al., 2017). These findings jointly indicate that motor cortex involvement is ubiquitous in semantic processing, regardless of the linguistic features of the stimuli.

The stronger involvement of the motor cortex in the L2 semantic processing, independent of its linguistic abstractness, allows us to speculate on its role in language processing more generally. The finding is in line with some previous studies showing greater motor activation in the L2 than the L1 (Monaco et al., 2021; Tian et al., 2020), though not exactly in the same time window (275 ms after onset in Monaco et al.'s study, 600 ms in the present study). The somewhat earlier emergence of the effect in Monaco et al. may arise from the use of single verbs, while in our study the stimuli were verb phrases, which are relatively more complex semantically, and may evoke longer-lasting cortical engagement. In addition, the semantic task in Monaco et al.'s study required explicit motor simulation, as participants needed to judge if the verb represents a physical or mental action. In contrast, the task in our study only required the evaluation of semantic congruency and did not require any action-related judgment. Although the underlying process in L1 and L2 may be different between Monaco et al.'s study and ours, both studies indicate stronger involvement of motor areas in L2.

However, there are also contradictory findings. The results of Vukovic and Shtyrov's study (2014) pointed to greater involvement of the motor cortex in the L1 than the L2, indicated by stronger mu rhythm ERD. This apparently opposite pattern may at least partly be due to the differences in the brain activation measures. ERD (and event-related synchronization) reflects the temporal changes in the power of oscillations, and particularly the 10-20 Hz (hence mu rhythm) is often associated with the level of top-down inhibitory control. Unlike ERD, evoked responses, on the other hand, are time and phase locked to the onset of incoming sensory input and are likely to reflect a different source of neuronal activation. Particularly for the later stages of activation, evoked responses are likely to represent activation of a distributed network, the center of which is represented by the spatial extent of the source model. In their study, Vukovic and Shtyrov interpreted the stronger modulation for the L1 as the results of a more integrated perception-action circuit for the L1 lexical-semantic representation and a higher degree of embodiment for the L1. An alternative interpretation of their findings may, however, be that even though the task did not require verbal output, L1 more readily and automatically engages articulatory preparation, which may manifest as stronger predictive (i.e., top-down) allocation of resources in the motor areas. This interpretation would be in line with the results of anticipatory alpha modulation in visual and language domains (Wang et al., 2018) and challenges the embodied interpretation of the findings. The stronger and automatic recruitment of motor representations in the L1 in early time windows would also be compatible with increased engagement of motor areas in the L2 in later time windows (as shown in our study). Indeed, given the strongly time-evolving nature of language processing in the brain, it is conceivable that the role of the motor cortex may vary across time. As the source result shows in our study, the activation in the L1 (but not the L2) extended to the precentral sulcus in 300-500 ms, although the difference between L1 and L2 did not show statistically significant clusters.

The discussion of the role of the motor cortex in language comprehension may thus need to be approached with increased resolution (both temporally and spatially), as different neuroimaging modalities, and even different neural measures derived by same modality suggest divergent roles. It is also of crucial importance to acknowledge the time-varying nature of language processing. In addition to the methodological concerns, the search for functional significance of motor cortex also requires rigorous use of reasoning in interpreting the neuroscientific findings. Indeed, it needs to be noted that the greater degree of motor cortex activation may not necessarily imply a higher degree of embodiment. As has been pointed out, the involvement of a certain cognitive process cannot be unequivocally inferred from the presence of brain activation of a certain region (cf. reverse inference, e.g., Henson, 2006; Mahon & Hickok, 2016; Poldrack, 2006), as a particular brain region may carry multiple cognitive functions with a primary or secondary role.

The difficulty in specifying the correspondence relationship between brain regions and cognitive functions also applies to neuroimaging studies concerning action-related language processing. Neural activation of the motor cortex has mostly been elucidated as the result of utilizing the motor cortex for mentally simulating action-related meaning. The inference is made based on the established fact that the motor cortex is engaged in motor execution, motor planning, and motor imagery, as has been widely reported (Filimon et al., 2007; Hanakawa et al., 2008; Leonardo et al., 1995). Consequently, motor activations in the studies of semantic processing are believed to indicate the engagement of the motor cortex in the mental simulation of action-related meanings. However, the motor cortex, in addition to its motor-related cognitive functions, has also been shown to be functionally involved in other cognitive processes in a sub-dominant way, including (procedural) memory retrieval, cognitive control, inhibition, and integration (Francis, 2005; Miller, 2000; Mofrad et al., 2020; Lambon Ralph et al., 2017; Ullman, 2004; Willems et al., 2010). In the context of language processing, as mentioned in Maieron et al.'s (2013) study, the engagement of the primary motor cortex may be related to other aspects of cognitive processing rather than specific linguistic processing, which was inferred based on the lack of modulation of language-motor coupling during the action-verb generation task for both lesion and healthy groups.

In the present study, greater activation of the motor cortex was found for the L2 than the L1 across conditions. Referring to the above reasoning, we are of the opinion that the greater activation of the motor cortex may not imply a greater degree of embodiment in the semantic processing of the L2, but a higher demand for cognitive resources to compensate for its lower proficiency and weaker semantic representation compared with the L1. The interpretation is made based on the joint findings of the underactivation of the language areas (short insular gyri and planum polare of the superior temporal gyrus) at the semantic processing stage and the overactivation of the motor area (central sulcus) at the post-semantic processing stage in L2, compared with L1. The planum polare of the superior temporal gyrus, as part of the anterior temporal lobe, has been shown to be a semantic hub for integrating domain-specific concepts and semantic integration in general (Lambon Ralph et al., 2017; see review by Visser et al., 2010). Interpreted in the context of the present study, the L1 with richer semantic representation (compared with the L2) is likely to engage a greater degree of the anterior temporal lobe for meaning processing. In contrast, the weaker semantic representation of L2 may cost longer time for participants to access the meaning of L2, which might account for the early underactivation in language areas. The motor cortex was over-recruited, presumably, to offset the inadequate engagement of language areas, as a result of weaker semantic representation of L2, compared with L1. However, it is important to collect more direct evidence on the causal role of language and motor areas in linguistic tasks, as neuroimaging studies are necessarily correlative in nature.

Similar interpretation about the compensatory mechanism has also been reported in a study of individuals with dyslexia (Richlan et al., 2011), where underactivation in the left temporal region and overactivation in the motor cortex was found in adults with reading difficulty. This lends support to the idea that motor areas may represent general supportive functions in case of lower proficiency. Indeed, it has been validated by converging empirical evidence, that the retrieval of weakly encoded information relies more strongly on the control network (Lambon

Ralph et al., 2017). Based on the above discussion, we argue that the greater activation of the motor cortex in the L2 may not signify a higher degree of embodiment, but a higher demand for cognitive resources to compensate for the inadequate engagement of the language network.

#### Functional Role of the Motor Cortex

By clarifying the role of learner-specific (i.e., language proficiency) and stimulus-specific (i.e., abstractness) factors, our findings shed light on the functional role of the motor cortex in language processing. There has been a longstanding debate on the functional and epiphenomenal role of motor cortex involvement in the literature on embodied language processing (Bocanegra et al., 2017; Desai et al., 2015; Fernandino et al., 2013; García et al., 2019; Reilly et al., 2019; Repetto et al., 2013; van Elk et al., 2010; Vukovic et al., 2017). Similar to our paradigm, some earlier studies attempted to disentangle these two roles by referring to the time course of the motor cortex activation, compared with that of the language areas (García et al., 2019; Papeo et al., 2009; Reilly et al., 2019; van Elk et al., 2010). The motor-related activations or modulations occurring at an early stage of semantic processing (130–190 ms post-stimulus in García et al., 2019; 300 ms in Reilly et al., 2019; 400 ms in van Elk et al., 2010) are considered as evidence supporting the assumption of the functional (i.e., necessary) role, which claims that the motor cortex directly contributes to semantic processing, while activations occurring at a later stage are considered to reflect post-semantic motor imagery (500 ms in Papeo et al., 2009) and not necessarily contributing to language comprehension.

However, the onset of semantic processing is unlikely to be clearly defined by a fixed time point, and it may vary considerably depending on learner-related factors (e.g., language proficiency and language experience) and language-related factors (e.g., language distance). For a less proficient language, the latency of lexical-semantic retrieval and integration can be delayed compared with the highly proficient native language. Considering the influence of language proficiency, we assume that the greater activation of the motor cortex in the L2 in our study is not the result of post-semantic motor imagery but reflects the general cognitive processes that support semantic processing in an indirect way. It may thus be useful for the discussion of the functional or epiphenomenal role of the motor network to focus not only on latency of motor cortex activation, but also on language proficiency, which may lead to variance in the latency of semantic access.

#### The Null Effect of Abstractness

Our study did not reveal any significant effect of abstractness, suggesting that neural responses in the motor areas may not be modulated by the degree of abstractness of the linguistic input. The finding is inconsistent with our prediction of decreased motor involvement with the increase of abstractness. Our finding is also inconsistent with previous studies exploring the effect of abstractness on a continuum (i.e., literal, metaphorical (idiomatic), and abstract; Desai et al., 2013; Tian et al., 2020). In their studies, hierarchically attenuated motor activation was found with the increase of linguistic abstractness.

So far, most studies concerning the effect of abstractness on motor cortex involvement mainly focused on literal and figurative action-related language (mainly metaphorical and idiomatic). Some revealed greater involvement of motor cortex for literal than figurative language (Cacciari et al., 2011), and some reported a similar degree of motor cortex involvement between them (Boulenger et al., 2009; Boulenger et al., 2012). Inconsistently, some other studies found motor cortex involvement only for the literal language, but not for the figurative

(Raposo et al., 2009). The discrepancy in findings may derive from methodological differences across studies, including task demands (covert vs. overt motor association), stimulus properties (word vs. phrase vs. sentence), and ways of presentation (word-by-word vs. whole item, visually vs. aurally). As has been highlighted, the recruitment of the motor cortex in action semantic processing is task (Giacobbe et al., 2022; Tomasino et al., 2008) and context dependent (Raposo et al., 2009).

Moreover, current findings call for a reflection on the relationship between artificial categorization of abstractness and its actual brain response. Although the stimuli do follow a linguistically defined continuum of abstractness, the actual brain responses may not follow such gradation. In future studies, it will be important to test the modulatory effect of abstractness on the degree of motor cortex recruitment by using comparable approaches.

#### Limitations

Our study has some limitations. First, our study is a correlative study in nature, and interpretations are mainly "bound" to earlier literature. Second, our study only included ROI-based analysis motivated by its hypothesis-driven nature. The exclusion of whole-brain analysis may cause the ignorance of important neural activity in other brain regions. Future studies should further investigate the relationship between language and motor networks in bilingual language processing by employing comparable approaches.

#### Conclusion

Our study explored the degree of involvement of language and motor areas modulated by language proficiency and linguistic abstractness. We reported an overall greater activation in the language areas for the L1 than the L2 at the semantic processing stage at 300–500 ms, and an overall greater activation in the motor regions for the L2 than the L1 at the later post-semantic processing stage at 600–800 ms. The over-recruitment of the motor areas in the L2 implied a compensatory role of the motor area to offset the lower language proficiency of the L2 in relative to the L1. Our study provides an alternative interpretation of motor cortex involvement in language processing and invites further research to explore the factors that modulate this relationship.

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#### AUTHOR CONTRIBUTIONS

Lili Tian: Conceptualization; Formal analysis; Investigation; Writing – original draft; Writing – review & editing. Hongjun Chen: Conceptualization. Pyry Petteri Heikkinen: Formal analysis. Wenya Liu: Formal analysis. Tiina Parviainen: Conceptualization; Resources; Writing – review & editing.

#### DATA AND CODE AVAILABILITY STATEMENTS

The data are not publicly available due to the restrictions of research ethics stated in the Privacy Notice for Research Subjects in terms of the privacy of research participants.

The data that support the findings of this study are available upon reasonable request from Tiina Parviainen (tiina.m.parviainen@jyu.fi) and Lili Tian (litian@jyu.fi).

In compliance with the General Data Protection Regulation, the following situation will be approved when requesting the data: (1) actions aiming to confirm and verify the validity and authenticity of the results of the current research; (2) actions related to scientific research or other compatible purpose.

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III

# SPATIOTEMPORAL DYNAMICS OF ABSTRACT CONCEPT PROCESSING: AN MEG STUDY

by

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