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Original Paper

The Role of the Left Middle Temporal Gyrus in the Semantic Processing of Nouns and Verbs in Chinese: A Transcranial Direct Current Stimulation Study

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Abstract

Vocabulary processing is an important cognitive function of human beings. Nouns and verbs are core word classes that support languages, and the differences in neural mechanisms of semantic processing between the two word classes have received a lot of attention. An important language processing area, left middle temporal gyrus (LMTG), has attracted a lot of attention because of its significant role in language processing. However, there is controversy about the role of LMTG in the semantic processing of nouns and verbs, and few related studies were based on Chinese, an ideological language. With the aid of transcranial direct current stimulation (tDCS), the current study investigated the role of LMTG in the semantic processing of Chinese nouns and verbs. Results showed that after receiving anodal-tDCS stimulation over LMTG, participants' semantic processing performance of Chinese verbs was significantly promoted. At the same time, such changes were not observed in the noun and number processing. Meanwhile, compared with concrete verbs, participants' semantic processing performance of abstract verbs was improved more. We concluded that LMTG played an important role in the semantic processing of Chinese verbs, especially abstract verbs.

Keywords

left middle temporal gyrus, noun, verb, semantic processing, transcranial direct current stimulation

1. Introduction

Words can be categorized into distinct classes based on the meanings they convey and the grammatical functions they serve within sentences (Elli et al., 1999). A fundamental distinction that exists universally across languages is the one between nouns and verbs. Nouns are typically used to identify specific entities, while verbs are employed to narrate events that occur over time and to illustrate the relationships between them (Croft, 2005). Significant differences between nouns and verbs in semantics have sparked the interest of scholars in many disciplines like psycholinguistics, neuropsychology, medicine, and language acquisition. Therefore, the question of whether there were neural distinctness for semantic processing between nouns and verbs has been explored by them.

Advanced neuroimaging techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have been utilized to explore the neural basis underlying the semantic processing of nouns and verbs (Tyler et al., 2001; Sörös et al., 2003; Bedny & Thompson-Schill, 2006). Neuroimaging techniques offered a unique window into the brain, enabling researchers to visually and instantaneously discern the brain regions that were activated during language processing. Besides, electroencephalography (EEG) and event-related potentials (ERPs) which can offer millisecond-level precision in capturing nuanced neural activity within targeted brain regions have been extensively employed. Some studies showed the same cortical activation for noun and verb processing in the tasks of semantic categorization, lexical decision, and picture naming (Tyler et al., 2001; Sörös et al., 2003). In contrast, a body of neuroimaging studies identified cortical regions that were preferentially recruited during either the semantic processing of verbs or nouns in alphabetic languages, showing that the left inferior frontal gyrus, middle temporal gyrus, superior temporal gyrus, and precentral area responded more to verbs, while left fusiform gyrus, inferior parietal lobule, and right cerebellum responded more to nouns using PET and fMRI. (Bedny & Thompson-Schill, 2006; Kemmerer et al., 2008). A consensus regarding the underlying neural basis for the semantic processing of nouns and verbs have not been reached.

In order to make clear whether noun and verb semantic processing are served by distinct neural mechanisms, studies have been actively exploring cortical areas that are specifically relevant to noun or verb processing, but results are still equivocal. Among these category-specific regions, the left middle temporal gyrus (LMTG), an immediate vicinity of motion-sensitive region, has attracted a lot of attention because of its significant role in language processing. A great majority of studies have found that the LMTG responded more to verbs, as compared to nouns, adjectives, and non-linguistic stimuli across tasks encompassing semantic judgments and lexical decision, suggesting that LMTG might be a verb-specific area (Tyler et al., 2002; Bedny & Thompson-Schill, 2006; Berlingeri et al., 2008; Kemmerer et al., 2008; Yu et al., 2011; Bedny et al., 2012; Faroqi-Shah et al., 2018; Elli et al., 2018). For example, Bedny et al. (2012) compared the neural activity during noun and verb comprehension in congenitally blind and sighted individuals with the aid of fMRI. The result indicated that the LMTG was more active for all verbs than nouns, irrespective of visual-motion features. However, many studies showed similar activation of LMTG for verb and noun processing (Perani et al., 1999; Shapiro, 2006). Therefore, there is controversy about the role of LMTG in the semantic processing of nouns and verbs.

Previous studies have predominantly focused on the role of LMTG in the processing of nouns and verbs by treating each word class as a whole. However, little noticed that the LMTG may exhibit different roles within individual word classes, hinting at a more nuanced and complex involvement in linguistic processing. Although stronger activation of LMTG related to the semantic processing of abstract words compared to concrete words has been proved by many fMRI experiments (Pexman et al., 2007; Wang et al., 2010), considerable controversy still exists. For example, The fMRI study of Kichl et al. (1999) found that the neural network involving LMTG was significantly activated for both concrete and abstract word processing compared with baseline. Therefore, it is necessary to explore the role of LMTG in the semantic processing of concrete and abstract words within nouns and verbs.

Studies exploring the role of LMTG in the processing of the two word classes were mostly based on alphabetic languages like English and German. Nevertheless, as an ideological language, Chinese has a complex spatial structure in which a character is combined with hierarchically organized radicals, making the mechanism of language processing may be different from that of alphabetic characters (Bolger, Perfetti, & Schneider, 2005). In China, the research on neural mechanisms of verb and noun processing started relatively late, and views on the role of LMTG in the semantic processing of the two word classes in Chinese were different (Yu et al., 2011; Wang & Yang, 2017; Yang et al., 2017). Yu et al. (2011) found that LMTG was more sensitive to verbs than nouns. The fMRI study of Wang and Yang (2017) showed that compared with noun processing, LMTG was triggered greater activation in verb processing of English and Chinese by examining the lexical representation of nouns and verbs in Chinese-English bilinguals. In contrast, several studies showed similar activation of LMTG induced by Chinese noun and verb processing (Yang et al., 2017). So, as a key region for Chinese word processing, the role of LMTG in the semantic processing of nouns and verbs in Chinese should be studied further.

Neuroimaging techniques like fMRI and EEG/ERP have been most commonly used in previous relevant studies. Although these techniques can display brain regions activated during language processing, they cannot explain the causal relationship between the activity of a specific brain region and language processing behaviors. Transcranial direct current stimulation (tDCS), a non-invasive stimulation technique, is able to change the cell membrane potential of neuronal cells in the specific brain area by means of a weak electrical current of 1-2mA to accelerate or weaken the release of neurotransmitters between neuronal cells, thus causing an increase or a decrease in neuronal excitability within a certain period of time (Ghasemian-Shirvan et al., 2020; Nitsche & Paulus, 2000, 2001). According to studies exploring the effect of tDCS stimulation on the motor cortex, anodal stimulation was assumed to increase the excitability (Priori et al., 1998), while cathodal stimulation reduced it (Jacobson, Koslowsky, & Lavidor, 2012). Recent years, tDCS has been applied to the research of verbal functions, and the evaluation in performance of language task induced by anodal-tDCS stimulation over some language areas like the posterior temporal cortex has been demonstrated (Sparing et al., 2008; Rivera-Urbina et al., 2022). Given that anodal stimulation of tDCS over language areas has been considered as a way to improve verbal recognition (Heimrath et al., 2020), it was applied to the the current study to modulate the cortical excitability of LMTG and explore the relationship between the activity of LMTG and language processing behavior, showing the role of LMTG in a better and more obvious way.

Therefore, using tDCS and adopting semantic judgment tasks and numerical judgment tasks, the current study aims at investigating the role of LMTG in the semantic processing of nouns and verbs in Chinese. In addition, the role of LMTG in the semantic processing of concrete and abstract words within nouns and verbs in Chinese will be further explored.

2. Method

2.1 Participants

21 healthy participants (9 males and 12 females, range from 18 to 24 years old) from Southwest Petroleum University were recruited in the current study. All participants were native speakers of Chinese and right-handed. They were screened by tDCS exclusion criteria and therefore had normal vision or corrected to normal vision, no history of epilepsy, brain disease, and mental illness, no head trauma, and no alcohol or drug abuse. Written informed consent was obtained from all the participants before they took part in the study. After the experiment, they received remuneration.

2.2 Materials

The stimulus materials used in the study were Chinese disyllabic words and three-digit numbers. For language materials, 1024 words used in the experiment were selected from the modern Chinese balanced corpus of the National Language Committee, including 256 concrete nouns, 256 abstract nouns, 256 concrete verbs, and 256 abstract verbs. There were 64 semantically associated word pairs in each word class, and every word pair was combined with two words containing different meanings of the same word class to form a trail. Therefore, 256 trials of semantic judgment tasks were formed and then divided into two sessions evenly. For number materials, four three-digit numbers were formed a trail. And then, 128 trials of numerical judgment tasks with similar difficulty to semantic judgment tasks were divided into two sessions evenly.

In order to diminish the effect of irrelevant variables, strokes, frequency, and imageability of verbs should be brought into line with nouns in the two experimental sessions. The mean strokes of nouns is 17.15, and verbs 17.15. The mean word frequency is 14.12 per million for nouns and 13.45 per million for verbs. Average imageability is 3.59 for nouns and 3.27 for verbs rated by 11 students who didn’t participate in the experiment in terms of Likert scale of 7 levels. Besides, concrete words and abstract words were roughly matched for strokes and word frequency in each word class, but had significant difference in imageability. In addition, the four words used in each trial were matched for imageability, strokes, and word frequency. Tasks in one session were roughly matched with tasks in the other session in difficulty.

2.3 Experimental Session Design

The experiments were divided into two parts and carried out in 3 days (see Figure 1). On Day 1, participants who were selected received behavioral training about the semantic and numerical judgment tasks. Then, in the second part, each participant took part in two sessions of formal experiments. On Day 2, participants received 20 minutes of anodal or sham stimulation of tDCS and then they were asked to perform semantic judgment tasks and numerical judgment tasks. One week later, participants took part in the second session in which they received a different type of stimulation from the one they received in the first session and then performed semantic judgment tasks and numerical judgment tasks. The order of tDCS stimulation were counterbalanced across all participants.

2.4 Tasks

Tasks were presented by a PC with E-Prime 2.0 software (Psychology software; Psychology Software Tools). The study adopted the semantic judgment tasks and numerical judgment tasks (see Figure 1) as paradigms according to previous studies. There were four blocks (192 trails), and each block contains 8 trails of concrete noun semantic judgment tasks, 8 trails of abstract noun semantic judgment tasks, 8 trails of concrete verb semantic judgment tasks, 8 trails of abstract verb semantic judgment tasks, 16 trails of numerical judgment tasks. Semantic tasks and numerical tasks appear alternately.

In semantic judgment tasks, there were 4 different words shown on the screen in each trial: the probe word (e.g., “铅笔”, in English, pencil), the target word (e.g., “橡皮”, eraser in English), and the two unrelated words (e.g., “肥皂, 河流”, soap and river in English). The numerical judgment task was roughly matched with the semantic task in difficulty. In numerical judgment task, there were 4 different three-digit numbers shown on the screen in each trial: the probe word (e.g., “175”), the target number (e.g., “168”), and the two other numbers (e.g., “185, 194”).

Before the first block was presented, a cross (3000 ms) appeared first. Following that, the first block including semantic and numerical judgment tasks began to present. In semantic judgment tasks, subjects were required to select a target word that was most related in meaning to the probe word which was shown on the upper half of the screen from three words presented underneath by pressing a key quickly and accurately. In numerical judgment tasks, subjects were required to choose which of the three choice numbers was closest in value to the probe number by pressing a key quickly and accurately. After pressing the key or no response within 3000 ms, it automatically entered the next trail.

2.5 TDCS Stimulation

TDCS was delivered via a pair of soaked sponge electrodes (5 cm diameter) by using a current stimulator (DROIAN, 2019A). During the stimulation, the anode electrode was placed at T3 (LMTG) according to the 10-20 international system, and the cathodal electrode was placed over the Fp2 (left orbit). A constant current of 2 mA was applied for 20 min (fade in 30 s and fade out: 30 s) for anodal stimulation. In the sham stimulation, there was a short direct current of 60 s (30 s fade in and 30 s fade out) at the beginning and end of the stimulation. There was no direct current stimulation after the first 60 s, except for small pulses of 500 ms every 10,000 ms emitted by the stimulator for impedance checking. The total current over time is not more than 100 μA.

2.6 Statistical Data Analysis

Reaction time (RT) and accuracy rate (ACC) of participants were measured and collected by E-Prime 2.0 software during the experiment and analyzed by IBM SPSS Statistics 26 after that. Before analysis, data of RT values were screened. Trails which were given wrong responses and correct trials with RT deviating more than 3 standard deviations from the participant's RT mean value were discarded.

Repeated measures ANOVA (Bonferroni corrected) was conducted with stimulation types (sham and anodal stimulation), tasks (noun, verb, and number judgment tasks), and concreteness of words (abstract and concrete words) as within participant variables. Besides, Post hoc t test was conducted to compare the RTs and ACC between two stimulation types within each task.

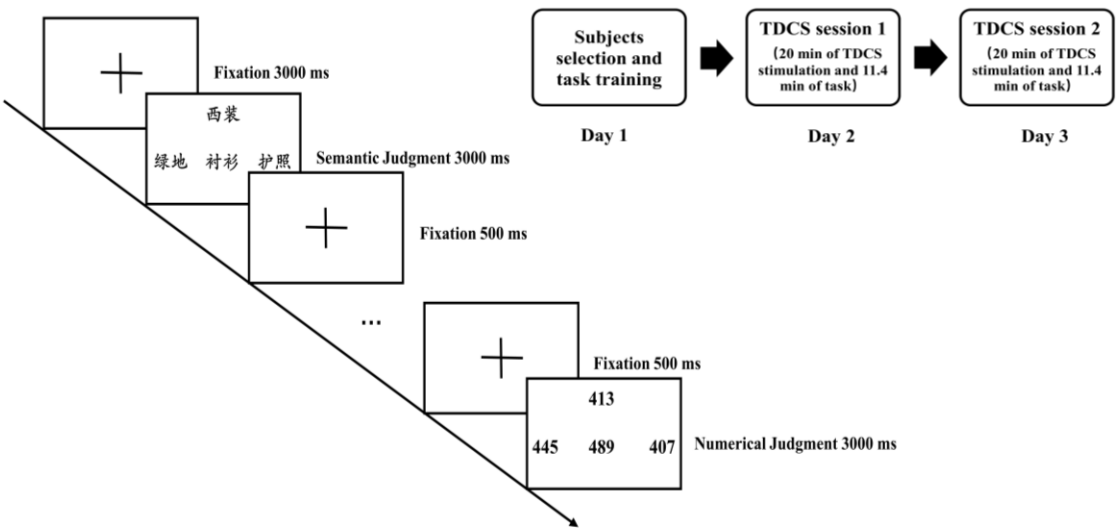

Figure 1. Experimental Tasks and Session Design

3. Result

Participants' RTs and ACC induced by tDCS effect were shown in Figure 2 for semantic and numerical judgment task respectively.

3.1 tDCS-induced Changes in RTs

A 2 (anodal stimulation vs. sham stimulation) × 2 (noun vs. verb semantic judgment task) two-way repeated measures ANOVA was conducted to reveal the influence of stimulation type and task on participants' mean RTs. It showed the significant main effect of neither task nor stimulation type. The significant interaction of stimulation type and semantic judgment task was observed [$F(1, 20) = 7.634$, $p = 0.012$]. Following that, pair-wise t-tests were conducted to make direct comparisons of RTs between two simulation types within two tasks. Result indicated that RTs significantly decreased when participants processed Chinese verbs in anodal stimulation condition compared with that in sham stimulation condition [$t(20) = 2.114$, $p = .047$]. There were no significant difference of RTs between two simulation types in the processing of Chinese nouns.

A 2 (anodal stimulation vs. sham stimulation) × 2 (noun vs. numerical judgment task) two-way repeated measures ANOVA only showed the main effect of task [$F(1, 20) = 60.262$, $p < 0.001$], indicating that participants spent longer time on number processing than semantic processing.

A 2 (anodal stimulation vs. sham stimulation) × 2 (concrete vs. abstract word) two-way repeated measures ANOVA conducted within noun showed the significant main effect of the concreteness of words [$F(1, 20) = 9.979$, $p = 0.005$], which revealed that participants' RTs were significantly longer in abstract noun processing compared with that in concrete noun processing. No significant main effect of stimulation type and interaction was discovered.

A 2 (anodal stimulation vs. sham stimulation) × 2 (concrete vs. abstract word) two-way repeated measures ANOVA conducted within verb revealed not only the significant main effect of the stimulation type [$F(1, 20) = 4.521$, $p = 0.046$] and concreteness of words [$F(1, 20) = 30.023$, $p < 0.001$] but also the significant interaction of the two factors [$F(1, 20) = 5.536$, $p = 0.029$]. Firstly, the result suggested that participants' RTs were significantly longer in abstract verb processing compared with that in concrete verb processing. Besides, participants spent less time on performing the two kinds of tasks in the anode stimulation condition compared with the sham stimulation condition. Pair-wise t-tests comparing the RTs between two stimulation types within concrete verb and abstract verb processing tasks were made respectively. Result indicated that RTs significantly decreased when participants processed Chinese abstract verbs in anodal stimulation condition compared with the sham stimulation condition [$t(20) = 3.128$, $p = 0.005$].

3.2 tDCS-induced Changes in ACC

A 2 (anodal stimulation vs. sham stimulation) × 2 (noun vs. verb judgment task) two-way repeated measures ANOVA didn't show significant main effect or interaction.

A 2 (anodal stimulation vs. sham stimulation) × 2 (noun vs. numerical judgment task) two-way repeated measures ANOVA showed the main effect of task [$F(1, 20) = 20.673$, $p < 0.001$], indicating that participants' ACC was lower in number processing compared with that in semantic processing.

A 2 (anodal stimulation vs. sham stimulation) × 2 (concrete vs. abstract word) two-way repeated measures ANOVA conducted within noun didn't show significant main effect or interaction.

A 2 (anodal stimulation vs. sham stimulation) × 2 (concrete vs. abstract word) two-way repeated measures ANOVA conducted within verb didn't revealed significant main effect or interaction.

Table 1. The Average RT (ms) in Semantic and Numerical Judgment Task

	Sham Stimulation	Anodal Stimulation
Noun	1340.04 (32.824)	1327.80 (34.130)
Verb	1378.17 (33.267)	1321.84 (29.766)
Number	1554.01 (44.924)	1556.53 (47.052)
Concrete Noun	1310.47 (29.296)	1312.16 (32.744)
Abstract Noun	1370.61 (37.855)	1345.23 (38.576)
Concrete Verb	1318.61 (31.498)	1300.42 (32.236)
Abstract Verb	1439.45 (39.177)	1343.66 (30.471)

Table 2. The Average ACC (%) in Semantic and Numerical Judgment Task

	Sham Stimulation	Anodal Stimulation
Noun	97.29 (0.594)	97.81 (0.486)
Verb	97.43 (0.653)	96.29 (0.731)
Number	95.76 (0.436)	95.76 (0.577)
Concrete Noun	96.95 (0.829)	97.71 (0.684)
Abstract Noun	98.10 (0.534)	98.33 (0.480)
Concrete Verb	97.24 (0.810)	97.24 (0.746)
Abstract Verb	97.57 (0.792)	95.95 (0.748)

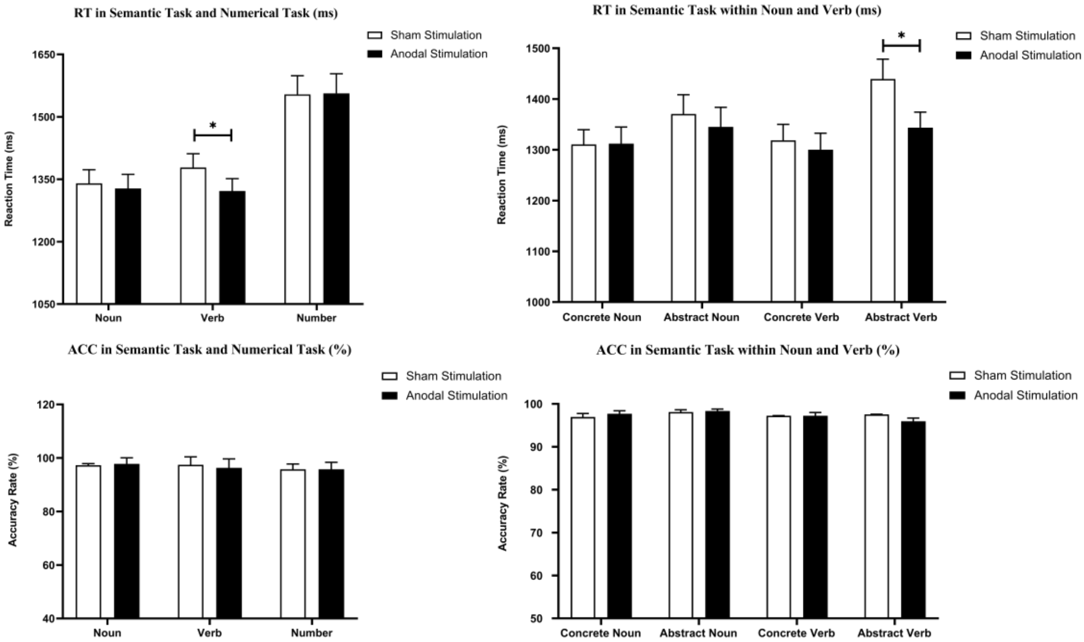

Figure 2. tDCS Effects. Reaction Time (RT) and Accuracy Rate (ACC) after tDCS Stimulation to LMTG in Semantic and Numerical Judgment Task. The Asterisk Means Bonferroni Corrected p < .05. Error Bars Denote SE.

4. Discussion

Adopting lexical semantic judgment tasks and numerical judgment tasks and applying tDCS, the current study aimed at exploring the role of LMTG in the semantic processing of Chinese verbs and nouns. Furthermore, the role of LMTG in the semantic processing of concrete and abstract words within each word class was explored. According to the data analysis of RTs, compared with the sham stimulation, anodal stimulation over LMTG largely promoted participants' response speed in semantic processing of Chinese verbs while such phenomenon was not found in noun and number processing. At the same time, within the verb, anodal stimulation over LMTG decreased participants' RT in the semantic processing of abstract verbs compared to sham stimulation more significantly. As native Chinese speakers, participants reached the "ceiling level" of ACC in semantic judgment tasks, and thus their ACC wasn't affected obviously by the changes of tasks and conditions. Therefore, the current study gave high priority to the RTs data which was able to show the effect of tDCS stimulation over LMTG on participants' performance consistent with a great number of previous literature.

4.1 The Role of LMTG in the Semantic Processing of Chinese Verbs

In the present study, the observation that anodal-tDCS stimulation over LMTG largely promoted participants' semantic processing performance of Chinese verbs rather than nouns and numbers is consistent with previous neuroimaging findings abroad and at home (Tyler et al., 2002; Bedny & Thompson-Schill, 2006; Yu et al., 2011; Bedny et al., 2012; Faroqi-Shah et al., 2018; Elli et al., 2018). Besides neuroimaging techniques, transcranial magnetic stimulation (TMS), one of the non-invasive stimulation techniques, has been used to stimulate the LMTG of subjects to realize the virtual damage of local brain functions and investigate the role of LMTG in the semantic processing of nouns and verbs (Papeo et al., 2015). It was found that TMS would lead to selective degradation of the semantic processing performance of verbs rather than nouns. In China, the fMRI study of Wang and Yang (2017) examined the lexical representation of nouns and verbs in Chinese-English bilinguals, showing that compared with noun processing, the LMTG was triggered greater activation in verb processing in both English and Chinese. Therefore, LMTG plays an important role in verbs processing in Chinese and some alphabetic languages like English. As a verb-responsive region, LMTG is involved in representing information about verb, enabling it to show different sensitivity to nouns and verbs (Bedny et al., 2012).

When it comes to theories concerning about the conceptual processing of nouns and verbs, embodied cognition theory is usually regarded as an influential view. The concept of "embodied cognition" was proposed by George Lakoff and Mark Johnson. In the 1980s, with the rise of the traditional cognitive science revolution, the second generation of cognitive science with "embodied cognition theory" as the core was proposed. From the perspective of embodied cognition theory, concepts of words are formed in the form of abstract cognitive representation in sensor-motor system based on perception-motion experience, and word comprehension requires simulation of the sensor-motion content described by words in the corresponding sensor-motor system which also takes part in the processing of actual or abstract objects or actions in the world, thus causing the activation of corresponding sensor-motor system in word comprehension (Gallese & Lakeoff, 2005). Studies have found that language comprehension and body perception-motion share some neurons. For verb processing, evidence from fMRI showed that sensor-motor cortices activated by verbs can be activated when these actions were performed (Hauk, Johnsrude, & Pulvermiller, 2004). Besides, when we talk about the noun "bananas", the shape, touch and taste of bananas will immediately emerge in the brain. It seems that we actually see, touch, eat, and smell a banana, and the corresponding sensor-motion cortices will be activated. The semantic processing of nouns and verbs are assumed to rely on the sensor-motion cortices based on previous evidence. Different features between noun and verb in various aspects enable the formation of partially distinct cortical networks of the two word classes.

As has been proved by previous studies and our study, the LMTG contains abstract representation of verb meanings. The reason of forming of this kind of representation has always been explored and "point of entry hypothesis" was proposed with the deepening of research. Point of entry hypothesis proposed that abstract amodal linguistic representations may be located in regions which were near the modality specific cortices from which prototypical members of that category were derived (Shapiro et al., 2006). According to the point of entry hypothesis, medial temporal/medial superior temporal cortex (MT/MST), sensory and motor modality-specific cortices, serves as "points of entry" for the acquisition of more abstract action knowledge, and abstract action concepts are represented within anterior or centripetal areas to the same modality-specific regions. Therefore, as a immediate vicinity of motion sensitive regions, LMTG, especially the posterior part of it had evolved into a region storing the knowledge about the visual attributes of actions (Bedny et al., 2008).

4.2 The Role of LMTG in the Semantic Processing of Concrete Verbs and Abstract Verbs

Our finding of different roles played by LMTG in the semantic processing of concrete and abstract verbs is consistent with previous evidence which showed that LMTG engaged more in the semantic processing of abstract verbs than concrete verbs. The role of LMTG in verb subcategories processing have been detected with the more sensitive fMRI measurement (Rodríguez-Ferreiro et al., 2010; Wang et al., 2010). The fMRI study of Rodríguez-Ferreiro et al. (2010) indicated that motion verbs caused less activation than abstract verbs in the LMTG. Wang et al. (2010) analyzed a number of fMRI and PET studies exploring the neural processing mechanisms of abstract and concrete words and found that LMTG responded more to abstract words than concrete word obviously. Therefore，it is reasonable that LMTG is recruited for both concrete and abstract verb processing and involved more in abstract verb processing.

Besides as a store for semantic attributes, LMTG has been claimed to be involved in the retrieval of semantic information when it comes to abstract and concrete concept processing (Corbett et al., 2009; Noonan et al., 2010; Davey et al., 2016). Both Rodríguez-Ferreiro et al. (2010) and Wang et al. (2010) argued that different activation in LMTG triggered by concrete and abstract verbs may caused by different retrieval processes and that abstract words may require more demand on semantic retrieval or integration because of less imageable representations, rather than less imageable representations being specifically stored or located in such region. The semantic networks of abstract verbs, which are less consistent and more diverse across stimulus items, resulting in less focalized, difficult to detect, distributed activity.

5. Conclusion

Using tDCS and adopting semantic judgment tasks and numerical judgment tasks, the current study firstly investigated the role of LMTG in the semantic processing of Chinese nouns and verbs, and result indicated that anodal-tDCS stimulation over LMTG significantly promoted participants' semantic processing performance of Chinese verbs rather than nouns and numbers. It suggests that LMTG mainly engages in the semantic processing of Chinese verbs rather nouns, which is consistent with previous findings. Together with available previous evidence, it is reasonable to claim that such word class effect is contributed to verb related semantic information represented by LMTG. Furthermore, the role of LMTG in the semantic processing of concrete and abstract verbs was explored, and the similar result as previous literature was gotten. According the result, LMTG was recruited both in the concrete verbs and abstract verbs processing while showed greater involvement in abstract verb processing owing to the greater demands on semantic retrieval or integration of abstract verbs. These findings are convergent with previous studies of alphabetic languages.

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