NEURAL REGENERATION RESEARCH
Volume 8, Issue 20, July 2013

www.nrronline.org

doi:10.3969/j.issn.1673-5374.2013.20.002 [http://www.nrronline.org; http://www.sjzsyj.org]
Wu QL, Chan YC, Lavallee JP, Chen HC, Chang KE, Sung YT. Processing Chinese hand-radicals activates the medial frontal gyrus: a functional MRI investigation. Neural Regen Res. 2013;8(20):1837-1843.

Processing Chinese hand-radicals activates the medial frontal gyrus

*A functional MRI investigation**

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Research Highlights

(1) Participants underwent functional MRI imaging while reading Chinese action verbs to elucidate the semantic representation of Chinese radicals.
(2) Reading characters with hand-radicals activated the right medial frontal gyrus.
(3) Verbs involving hand-action activated the left inferior parietal lobule, possibly reflecting integration of information in the radical with the semantic meaning of the verb.
(4) This study enhanced our understanding of the neural substrates underlying the process of reading in Chinese, with potential benefits for the development of treatments for dyslexia.

Abstract

Embodied semantics theory asserts that the meaning of action-related words is neurally represented through networks that overlap with or are identical to networks involved in sensory-motor processing. While some studies supporting this theory have focused on Chinese characters, less attention has been paid to their semantic radicals. Indeed, there is still disagreement about whether these radicals are processed independently. The present study investigated whether radicals are processed separately and, if so, whether this processing occurs in sensory-motor regions. Materials consisted of 72 high-frequency Chinese characters, with 18 in each of four categories: hand-action verbs with and without hand-radicals, and verbs not related to hand actions, with and without hand-radicals. Twenty-eight participants underwent functional MRI scans while reading the characters. Compared to characters without hand-radicals, reading characters with hand-radicals activated the right medial frontal gyrus. Verbs involving hand-action activated the left inferior parietal lobule, possibly reflecting integration of information in the radical with the semantic meaning of the verb. The findings may be consistent with embodied semantics theory and suggest that neural representation of radicals is indispensable in processing Chinese characters.

Key Words

neural regeneration; neuroimaging; functional MRI; hand-radical; radical representation; Chinese character recognition; embodied semantics; semantic function; Chinese learning; grants-supported paper; neuroregeneration

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Received: 2013-02-08
Accepted: 2013-05-11
(NY2012130001)

Funding: This work was supported by a grant from Ministry of Education, Taiwan, China under the Aiming for the Top University Plan at Taiwan Normal University, China.

Author contributions: Wu QL and Chan YC collected and analyzed the data and wrote the initial draft of the manuscript. Lavallee JP assisted in literature review and discussion as well as manuscript revision. Chen HC designed this study. Chang KE and Sung YT monitored and supervised all aspects of the study. All authors approved the final version of the paper.

Conflicts of interest: None declared.

Ethical approval: The study was approved by the Research Ethics Committee of National Taiwan University Hospital, China. All of the subjects gave their informed consent to participate before commencing the study.

Author statements: The manuscript is original, has not been submitted to or is not under consideration by another publication, has not been previously published in any language or any form, including electronic, and contains no disclosure of confidential information or authorship/patent application/funding source disputations.

INTRODUCTION

The ability to read Chinese characters is a complex skill and it requires considerable effort and time to master. Despite recent progress, the neural processes underlying this ability are still not completely understood. In particular, questions remain about the processing of semantic radicals. The majority of Chinese characters include radicals or classifiers containing distinct semantic content, but the processing of these components is poorly understood[1-7]. The present study focuses on two active brain areas of enquiry concerning the neural substrates of Chinese reading. First, this study extended applications of embodied semantics theory to Chinese by attempting to identify regions associated with the processing of semantic radicals. Second, this study discussed whether Chinese characters are read as individual components or as meaningful wholes.

Embodied semantics theory holds that semantic representations of action-related word and meanings are implemented through neural networks which overlap with or are identical to the sensory-motor networks involved in perception or action related to that meaning[1-7]. Consistent with embodied semantics theory, a number of studies in which patients with lesions to frontal pre-motor areas are included have identified deficits in action comprehension[8-9], although more mixed findings in this area have appeared as well[10]. In addition, imaging studies have revealed the activation of brain areas associated with perception or action during tasks involving reading of words with related semantic meaning[11-15]. For example, the mere passive reading of action verbs such as kick, pick and lick has been found to activate areas of the sensory-motor cortex associated with the legs, hands and face, respectively[14].

The theory of embodied semantics has also been applied to Chinese. Yang *et al* [15] had participants read Chinese hand-verbs and tool-use verbs. Half of the tool-use verbs used in the study contained radicals indicating hand involvement, while the radicals in the other half represented tools. They found that reading both types of verbs resulted in activation of hand-use related areas of sensory-motor cortex, while the tool-use verbs with hand-radicals additionally activated regions association with actual tool use (the left superior parietal lobule and left middle frontal gyrus). The tool-use verbs with tool radicals, when compared to the hand-use verbs, resulted in stronger activation in areas associated with tool naming and conceptual knowledge related to tools (the left posterior inferior and middle temporal gyri).

This raises a second issue, however. Semantic processing of Chinese characters may occur at the level of both the components and the whole character. That is, readers may recognize the character directly, or may recognize the distinct components first, and then combine them into a character[16]. To date, there is no consensus on whether the representation of the semantic meaning of radicals is a necessary step in the processing of Chinese characters. To date, there is no consensus on whether the representation of the semantic meaning of radicals is a necessary step in the processing of Chinese characters. A number of studies have shown that the semantic radicals in Chinese characters are processed separately as part of the character-recognition process[17-19]. However, it has also been found that, although the presence of radicals reduces the processing time required for low-frequency characters, it does not affect the time required for the identification of high-frequency characters[20-21]. This suggests that high-frequency characters are identified directly, without requiring an independent stage in which the meaning of the radical is represented. Further research is thus needed to determine whether representation of action-related characters activates regions in the sensory-motor cortex, and whether representations are developed for the components of characters, for whole characters, or for both.

The purpose of the present study, then, is to investigate the semantic processing of Chinese radicals and Chinese characters. To investigate whether radicals are processed independently even for high-frequency char acters, only high-frequency characters were selected. Characters for Chinese action verbs were first divided according to whether or not they contained a hand-radical (the classifier form of the character for hand, 手, contained in words such as 打 and 把). Then, they were divided again according to whether or not the semantic meaning of the verb actually included hand action. Participants were asked to read the characters in the resulting four categories while in a functional MRI scanner in order to further elucidate the processing of Chinese characters. Resulting levels of activation across the two conditions (characters with and without hand-radicals, and characters with and without meanings related to hand action) were subsequently compared.

RESULTS

Quantitative analysis of subjects

Twenty-eight healthy participants were initially included in this study and all of them entered the final analysis.

Effect of hand-radicals

The contrast analysis between the reading of characters containing the hand-radical *versus* characters not containing the hand-radical revealed that characters with hand-radicals elicited greater activity in the right medial frontal gyrus (Montreal Neurological Institute coordinates (x, y, z): 1, 56, 10; Z = 3.25, P < 0.001 uncorrected, 6 voxels; right medial frontal gyrus, BA10; Figure 1.

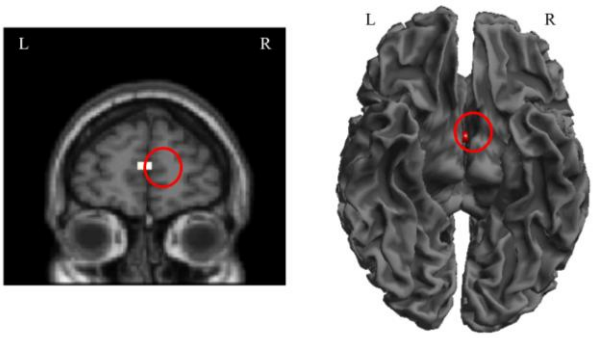

Figure 1 Hand-radical activated brain areas during character reading.

Greater activation (circle indicated) was found for the hand radical *versus* non-hand radical conditions in the right medial frontal gyrus. L: Left hemisphere; R: right hemisphere.

Effect of semantic hand action

The contrast analysis between characters for action verbs with meanings involving hand action *versus* those with meanings not involving hand action revealed that characters for verbs involving hand action elicited greater activity in the left inferior parietal lobule (Montreal Neurological Institute coordinates (x, y, z): –63, –37, 37; Z = 4.03, P < 0.001 uncorrected, 32 voxels; inferior parietal lobule, BA40). Results are shown in Figure 2.

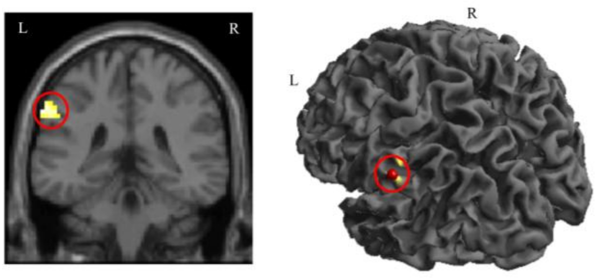

Figure 2 The reading of action verbs with meanings involving hand action activated brain areas.

Greater activation (circle indicated) was found for the semantic hand action *versus* non-semantic hand action conditions in the left inferior parietal lobule. L: Left hemisphere; R: right hemisphere.

DISCUSSION

This study tested the application of embodied semantics theory to the Chinese language system and examined the role of radical representation in the processing of high-frequency Chinese characters. Results revealed that processing characters containing hand-radical activated the right medial frontal gyrus while processing characters not containing hand-radical did not. Also, verbs with meanings related to hand action were associated with greater activation of the left inferior parietal lobe than verbs whose meaning did not involve hand action. Each of these findings is discussed in turn.

First, it was found that reading characters containing hand-radicals resulted in greater activation of the right medial frontal gyrus (BA 10). The right medial frontal gyrus is a part of BA 10, which is a very large cytoarchitectonic area, the functions of which remain poorly understood[22]. The posterior middle frontal gyrus overlaps the pre-motor cortex, and an earlier study of words representing arm movements found overlapping activation in this region for representations of arm-related verbs and for actual hand movement[14]. Given that BA 10 is a large area, it is conceivable that the present results are consistent with earlier research indicating a neural connection between sensory-motor cortex and semantic representation[1-11]. However, activation in the present study was more anterior than would be predicted by embodied semantics theory.

Another possible explanation for this finding emerges from one recent attempt to synthesize findings on the role of BA 10. According to the ‘gateway hypothesis,’ this region serves as a ‘gateway’ between stimulus-oriented and stimulus-independent attending[22]. In particular, the medial portion of BA 10 has been found to be active in situations requiring a greater degree of attention to external stimuli, while the lateral BA 10 region has been found to be active in situations for which internal representations need to be referenced or processed[23]. Thus, in classical ‘multi-tasking’ situations, this region is called on to perform a gate-keeping role, alternatively allocating attention between external and internal representations based on the agent’s developing goals and intentions. The present finding regarding activation of the medial region of BA 10 in response to all characters with hand-radicals suggests the possibility that characters containing radicals with related meanings (here, hand-radicals verbs involving hand action) may call forth a relatively greater degree of attentiveness. This enhanced level of attentiveness may serve to help readers to distinguish between different hand-related meanings by identifying the precise nature of the relationship between the character components. This account is consistent with the assumption that the components of characters are processed separately.

A second finding is that reading characters whose meaning involves hand action is associated with a greater degree of activity in the left inferior parietal lobule (BA 40) than reading of characters whose meaning does not involve hand action. This area of the brain has been associated with semantic integration[24-29]. Chou *et al* [27] found that processing character pairs with strong semantic associations resulted in greater activation in this region than did processing character pairs with weaker semantic associations. This study argued that more closely associated pairs of Chinese characters may call forth a greater amount of integrative activities because there are more overlapping features or because the shared features are more characteristic of the characters. Here, we suggest that the same logic may extend to the components of individual characters. It is possible that this area was active during reading hand-action verbs in the present study because half of these characters included a hand-radical and the semantic hand-action, resulting in more overlapping features requiring integration. These overlapping semantic representations may have required a greater degree of integration, resulting in stronger activation of the left inferior parietal lobule.

As with the first finding, this account is consistent with the assumption that semantic radicals are processed separately. It has been suggested that radicals may not be processed separately for high-frequency characters[21]. Here, it is important to note that only high-frequency characters were used in the present study and that our results are consistent with separate processing for these characters.

There were a number of limitations to the present study. First, the study used a passive reading task, asking participants to read and comprehend the characters that were individually presented to them. However, as different participants may engage the meaning of characters at different levels, levels of activation may vary across individuals. In further research, the use of lexical decision tasks may strengthen the depth of participant engagement with the stimuli. Also, analysis in this study is at the whole-brain level and not at the region-of-interest level. The whole-brain level was preferred because previous research had not consistently identified a distinct set of regions in which activation would be expected. A disadvantage to this approach, however, is that it offers a lesser degree of sensitivity to activations. Future studies might target particular regions, such as particular portions of the sensory-motor cortex, in further applications of embodied semantics theory to Chinese character processing.

A third point is that the study used a block design without filler items, due to a concern that the activation levels would be unlikely to achieve significance with an event-related functional MRI design. However, this raises the possibility of an atypical degree of attention being paid to the hand-radicals simply because they are common to the stimuli within a block. Future studies should consider an event-related design, perhaps with filler items. The present study also did not control the number of meanings per individual character. Future studies should consider doing so. Finally, this study examined only a single semantic radical. Radicals of Chinese characters have a wide variety of semantic meanings. Staying within the realm of semantic meanings related to sensory-motor processing, other radicals, such as mouth (口) and foot (足), could be used for future studies.

A final suggestion is that future studies of embodied semantics might also consider including conditions showing only hand-radicals (扌), the hand character (手), and actual hand movements. Comparison results across these conditions would make it possible to see whether they activate the same area (s) as characters with hand-radicals.

This study found that reading Chinese characters containing hand-radicals activated the right medial frontal gyrus. This activation may be consistent with embodied semantics theory, but other explanations are also possible. In particular, we noted the possibility that different combinations of semantic radicals and whole-character meanings may result in this region being called upon to play a 'gate-keeper' role, allocating more or less attention to discerning the precise relationship between different components of the character. The study also found that verbs representing hand-action were associated with greater activation of the left inferior parietal lobe than verbs not related to hand action, possibly due to the greater degree of integration required to assimilate the semantic information made available by the radical with the meaning of the verb itself. As only high-frequency characters were used in the present study, we note that both findings were consistent with the claim that semantic radicals are processed separately, even for high-frequency Chinese characters.

Finally, in terms of clinical significance, we emphasize that learning Chinese is a long and difficult process, with the prevalence of dyslexia for children learning to read Chinese possibly as high as 9.7%[30-31]. It is hoped that the present paper will contribute to the growing understanding of the neural substrates underlying the process of reading in Chinese, and that this will have eventual benefits for instruction.

SUBJECTS AND METHODS

Design

This study used a block functional MRI paradigm in the passive reading task. We employed a two (hand-radical: yes and no) by two (semantic hand action: yes and no) within-subject factorial design.

Time and setting

The study was performed at the Department of Medical Imaging of National Taiwan University Hospital, Taiwan, China between February and April, 2012.

Subjects

Twenty-eight neurologically healthy volunteers, 12 males and 16 females, aged 21–30 (mean 24.39 ± 2.60) years, were included in this study. All these volunteers were university undergraduate or graduate students and native-Chinese speakers. There were no contraindications to the agents used in the study. Participants were asked to refrain from ingesting caffeine and alcohol for the 24 hours preceding the experiment.

Methods

Stimuli

The experimental materials consisted of 72 high-frequency characters in traditional Chinese. The 72 characters were divided into four different conditions: (1) hand-radical verbs involving hand actions, such as zhua (grab), da (beat), and ti (lift); (2) hand-radical characters not involving hand actions, such as sun (lose), cuo (arrange), and juan (donate); (3) characters without hand-radicals for verbs involving hand actions, such as qu (take), shou (receive), and ju (lift); and (4) characters without hand-radicals for verbs not hand actions, such as chi (gallop), liu (flow), and tiao (jump). Each condition contained 18 characters. All characters came from the "Report on the Frequency of Words and Phrases in Chinese Dictionaries"[32]. Characters in the different conditions were matched for the number of strokes and frequency, as well as for their familiarity, concreteness and imageability based on ratings made by a separate sample of 18 participants (with demographic backgrounds similar to those in the main sample) using a 7-point likert scale (Table 1). All of the characters used in this study are presented in Table 2. As the frequency distribution was non-normal, we reported the log-adjusted frequencies of the characters in Table 2. High-frequency characters were defined as those with log-adjusted frequencies greater than 1, meaning that the characters occurred more than 100 times per every 10 000 000 characters.

Experimental paradigm

The present study employed a block design for the passive reading task. The task began with an 8 second rest followed by eight experimental blocks. Each stimulus was displayed for 2 seconds, followed by 0.5 second blank. The stimulus font was BiaoKaiti, font size was 60 large and the font color was white on a black background. Each block displayed nine single-character stimuli. Thus each block lasted 22.5 seconds and was followed by blank screen for 19.5 seconds (Figure 3). The eight blocks lasted 336 seconds. The order of the blocks was randomized.

Image acquisition

Images were acquired with a 3T scanner (Siemens Trio, Siemens Medical Solutions USA, Inc., Malvern, PA, USA) at National Taiwan University Hospital, Taiwan, China.

Table 1 Characteristics of experimental stimuli

Type	Familiarity	Concreteness	Imageability	Familiarity of radical	Strokes	Log-adjusted frequency
Hand-radical with hand action	6.35	5.62	5.88	6.45	10.89	4.01
Hand-radical without hand action	6.28	4.38	4.83	3.73	11.33	4.58
No hand-radical with hand action	6.41	5.72	5.91	5.91	11.17	3.83
No hand-radical without hand action	6.27	5.18	5.34	1.62	11.56	4.22

Table 2 Experimental stimuli with log frequencies

Hand-radical with hand action		Hand-radical without hand action		No hand-radical with hand action		No hand-radical without hand action	
Word	Log-adjusted frequency	Word	Log-adjusted frequency	Word	Log-adjusted frequency	Word	Log-adjusted frequency
握	4.77	技	5.82	拜	5.16	帽	4.09
拾	4.11	捐	4.09	收	4.80	恩	4.61
按	5.27	掉	5.36	炒	2.08	退	4.74
插	4.84	扮	3.89	簽	4.28	淋	3.33
拆	3.85	損	4.96	煮	3.43	疼	3.56
拔	4.43	搞	2.71	射	5.27	託	3.99
揉	2.56	擇	5.00	牽	4.23	胎	3.99
撈	2.83	捷	3.50	劈	2.64	針	4.91
掀	3.53	振	4.83	耕	4.44	慶	4.92
拍	5.31	拒	4.69	爬	4.63	躲	4.22
捏	2.83	抗	5.34	砍	3.37	淚	4.48
捉	4.62	捨	2.71	敲	4.36	娘	4.62
擦	4.52	擾	4.53	煎	2.77	腹	3.97
扭	3.33	探	4.79	刮	3.37	遲	4.82
撥	3.97	撤	4.66	奪	5.02	首	4.23
摘	3.22	批	5.23	釣	3.81	誇	3.56
抬	4.63	擴	5.24	斬	3.14	猛	4.48
捧	3.50	揚	5.09	綑	2.08	樑	3.40

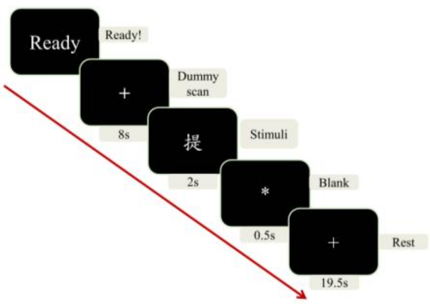

Figure 3 Procedure employed in the functional MRI experiment.

A gradient echo planar imaging sequence was used to acquire the functional images (34 axial slices) parallel to the anterior and posterior commissure, with the following parameters: repetition time = 2 000 ms, echo time = 24 ms, flip angle = 90°. The field of view was 256 × 256 mm^2, matrix size 64 × 64, thickness 3 mm without inter-slice gap, and voxel size was 4 × 4 × 3 mm^3. A T1-weighted MPRAGE sequence was used to acquire high-resolution anatomical images of the entire brain with the following parameters: repetition time = 1 560 ms, echo time = 3.68 ms, flip angle = 15°, field of view = 256 × 256 mm^2, and matrix size = 256 × 256; 192 sagittal slices; 1 × 1 × 1 mm^3 resolution.

Image analysis

Data were analyzed using SPM8 software (Statistical Parametric Mapping, Wellcome Department of Cognitive Neurology, London, UK). A supplementary whole-brain analysis was performed. In order to correct for subject motion, the images were realigned to the first volume. The movement was no more than 2 mm in any plane. Co-registered images were normalized to the standard Montreal Neurological Institute echo planar imaging template, and the 3 × 3 × 3-mm voxel size of the written normalized images. Statistical analyses were calculated on data that had been spatially smoothed using an 8-mm full-width-at-half-maximum Gaussian kernel, with a high-pass filter (128-second cutoff period) in order to remove low frequency artifacts.

Data from each participant were entered into a general linear model using a block-design analysis procedure. In the first-level analysis, we applieda *t*-test across all participants. All reported areas in the main effect of activation were considered significant at $P < 0.001$ uncorrected for multiple comparisons at the voxel level, with a cluster size greater than or equal to 6 voxels.

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(Reviewed by Lin CY, Hu JF, Zhang N, Wang LS)
(Edited by Li CH, Song LP, Liu WJ, Zhao M)