



# Neural Pattern Similarity in Chinese Character Processing Using Representational Similarity Analysis: A Review and Future Directions

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**Abstract.** It is important to explore the neural patterns involved in Chinese character processing since its learning poses major challenges for foreign language learners. However, most studies on this topic have relied on univariate activation analysis. Very few studies have adopted representational similarity analysis (RSA) that is able to capture fine-grained pattern differences even when regional-average differences are absent<sup>[1]</sup>. This paper systematically reviews studies using RSA and suggests that the Visual Word Form Area (VWFA) is crucial in Chinese character processing, as it simultaneously represents phonological, orthographic, and semantic information. Furthermore, the review proposes two directions for future research: (1) investigating how language-related factors affect neural patterns through a longitudinal design; and (2) exploring whether large language models (LLMs) process Chinese characters similarly to humans. This review provides theoretical support for advancing the understanding of the neural mechanisms involved in Chinese character processing and may contribute to the development of AI-assisted educational technologies and personalized learning tools for Chinese character learning.

**Keywords:** Chinese Character Learning, Representational Similarity Analysis, Visual Word Form Area.

## 1 Introduction

Currently, over 25 million people are learning Chinese worldwide. For the spread of Chinese language, it is important to understand the neural mechanisms involved in processing Chinese characters, so as to provide support for Chinese language education.

Previous studies have shown that several regions were activated during Chinese character processing, including the left middle frontal gyrus (MFG)<sup>[2,3]</sup>. In addition to univariate activation analysis, multivariate methods such as representational similarity analysis (RSA) offers advantages in capturing patterns of neural activity across multiple voxels and is able to detect the fine-grained pattern differences even in the absence of regional-average differences<sup>[1]</sup>. Previous studies have adopted RSA to explore the representation of Chinese characters in the brain. Critical aspects of Chinese character

representation have been investigated, including the representation of phonological information<sup>[4-6]</sup>, orthographic information<sup>[5-7]</sup>, and semantic information<sup>[8]</sup>.

Still, one critical gap remains, as indicated by Wu et al. (2012)<sup>[9]</sup> that Chinese character processing involves a common sub-network underlying the character recognition process regardless of the information component (phonology, orthography and semantics). Specifically, different information components are not processed independently, but interact with each other through complex neural networks. However, current studies mostly focus on one aspect of processing, such as phonological or semantic encoding, often in isolation. A comprehensive review of how these three types of information are represented in Chinese character processing is still in lack.

Thus, this paper provides a systematic review of how phonological, orthographic, and semantic information are represented in Chinese character processing, offering insights for future research on neural pattern similarity in Chinese learners using RSA. It also proposes new directions for future studies in order to advance research that integrates RSA with Chinese character processing and support international Chinese language teaching.

The present review intends to address the following questions: (1) How are phonological, orthographic, and semantic information represented in Chinese character processing for native Chinese speakers, as explored in current RSA research? (2) What directions can future research focus on?

## **2 Representation of Information in Chinese Character Processing by Native Chinese Speakers**

### **2.1 Representation of Phonological Information**

Chinese characters differ from alphabetic words in phonological processing. While alphabetic words' phonology is phonemic, the Chinese characters' phonology is defined syllabic<sup>[10]</sup>.

Previous studies have investigated how phonological information is represented in Chinese character processing by native Chinese speakers<sup>[4-6]</sup>. Li et al. (2022) investigated the role of MFG in Chinese character processing and whether regions responsible for phonological processing of alphabetic words (e.g., left superior temporal gyrus and supramarginal gyrus) are also involved in Chinese character processing. A reading aloud task was adopted. Phonological similarity matrices were generated using both a self-rating dissimilarity matrix and a computational model<sup>[11]</sup>. By correlating these with neural data, results revealed that the left middle and inferior frontal gyri and bilateral occipitotemporal areas represented phonological information of Chinese characters. Qu et al. (2022) investigated whether phonological demands influence information representation in the visual word form area (VWFA). They used both explicit and implicit reading tasks, which differ in phonological demands. The phonological dissimilarity matrix for stimuli was constructed based on the lexical constituency model<sup>[12]</sup>. RSA analysis revealed enhanced phonological representations in the VWFA during the explicit task compared to the implicit task, suggesting that phonological demands

modulate phonological representation in the VWFA. Zhao et al. (2017) made similar conclusions that the VWFA represented phonological information by correlating neuroimaging data and rating and computational models of phonological dissimilarity matrix.

To conclude, the phonological information is primarily represented in the MFG and the occipitotemporal areas. Additionally, phonological demands may modulate information represented in the VWFA in the occipitotemporal areas.

## 2.2 Representation of Orthographic Information

Chinese characters differ from alphabetic words in visual appearance and orthographic structure<sup>[13]</sup>. For instance, Chinese characters are made up of intricate strokes arranged in a square configuration, while alphabetic words are linearly combined letters.

Sublexical level of Chinese characters may modulate neural pattern similarity<sup>[14]</sup>. Liu et al. (2022) examined two measures of radical combinability: position-general radical combinability (GRC), which calculates the total frequency of a radical in different characters, and position-specific radical combinability (SRC), which accounts for the radical's position in a character. For example, the radical “黑” has a GRC of 16 and an SRC of 11 when placed on the left. They also measured the proportion of shared logographemes between word pairs, by calculating the ratio of shared logographemes to the total number of logographemes in both words. For example, “静” and “脏” share the logographeme “月”, resulting in a ratio of 2/7. The study found that only SRC significantly correlated with neural activity, with SRC encoded in the bilateral MFG and the superior parietal lobule (SPL). Additionally, logographeme composition was correlated with bilateral activity in the SPL.

Previous studies have also investigated how abstract orthographic information is represented in the brain<sup>[5,6]</sup>, investigating whether the VWFA is specific to orthographic processing or represents both orthography and phonology. Qu et al. (2022) found enhanced orthographic and phonological information in the VWFA during phonologically demanding tasks. Zhao et al. (2017) used the H-Max model, an object recognition model simulating neuronal responses to visual objects from lower to abstract levels, and discovered that both abstract orthographic and phonological information are represented in the VWFA. They also found that abstract orthographic information is increasingly represented from posterior to anterior in the VWFA, with the left and right hemispheres processing high- and low-frequency orthographic information, respectively.

Current literature suggests that the internal structure of Chinese characters influences neural pattern similarity in native speakers, and that abstract orthographic information is represented in the VWFA along with phonological information.

## 2.3 Representation of Semantic Information

To our knowledge, only one study has investigated the representation of semantic information during Chinese character processing in native speakers<sup>[8]</sup>. Wang et al. (2018) explored whether and how semantic information is represented in VWFA. The

taxonomic task involved categorizing words into groups like “animals” and “plants”, while the thematic task involved grouping words such as “dog” and “cat” under “animals”. Additionally, model matrices constructed by subjective semantic rating and word2vec model.

The study revealed that VWFA’s neural patterns are related to task-specific semantic information: in the taxonomic task, VWFA activity correlates with categorical information, while in the thematic task, it correlates with thematic information. Additionally, semantic distance between stimuli, measured by word2vec model, was significantly correlated neural patterns in both tasks. These results suggest that during Chinese character processing, VWFA also represents semantic information.

### **3 Future Directions for Investigating Chinese Character Processing Using RSA**

#### **3.1 Investigating Chinese Character Processing in Second-language Chinese Learners Using RSA**

Learning Chinese character is challenging due to its visual complexity, orthography, and phonology, which differ significantly from alphabetic words [4]. Therefore, it is important to investigate the neural pattern similarity during Chinese character learning across participants from different language backgrounds.

First, it is important to consider how language-related factors influence neural pattern similarity between Chinese learners and native speakers during Chinese character processing. Previous studies have shown that cross-language pattern similarity can be modulated by language-related factors, including word concreteness [15], semantic depth [16], and reading proficiency [17]. Notably, this review proposes that future studies regarding this issue could take more factors into consideration. For example, onset age of Chinese acquisition and estimated cumulative exposure to Chinese have been shown to modulate neuroplasticity [18,19]. Thus, it is crucial for future studies to explore whether these two factors affect the neural pattern similarities between Chinese learners and native speakers during Chinese character processing.

A longitudinal design could also be adopted. Few studies have done so, and existing ones often have short tracking periods. Thus, future studies could extend the tracking time to better capture the changes in neural pattern similarity during learning.

#### **3.2 Aligning Artificial Intelligence (AI) with Neural Pattern Similarity in Chinese Character Processing**

With the rapid development of AI, it is crucial to study how AI processes Chinese characters. Future research should focus on how large language models (LLMs) like ChatGPT and DeepSeek, represent Chinese characters and whether their processing resembles human cognition. RSA is an ideal tool to investigate this issue, as it is able to transform complex neural activity and LLM response patterns into vectors, enabling comparisons of similarities in a high-dimensional representation space. This approach

can reveal both the commonalities and differences between systems in how they process information.

Based on this, an interesting line of research concerning this topic is to compare LLMs with sensorimotor learning experience and those without such experience, and see whether they differ in their alignment with human neural patterns during Chinese character processing. Recent advances in LLMs have provided such avenue to test this question. While most LLMs were trained based on vast amounts of language inputs<sup>[20]</sup>, recent models have integrated sensorimotor learning during the training process instead of training with language input alone. For example, ChatGPT4 was trained based on both language and visual input modalities. Despite that all models displayed human-like cognitive performances, models with sensorimotor learning experience exhibited enhanced similarity with human representations, especially in visual domains<sup>[21]</sup>.

As a result, it will be intriguing to investigate whether LLMs with different training methods will exhibit differential alignment with human representation during the processing of visually complex Chinese characters using RSA. By investigating this question, innovative teaching methods can be fostered. Tools for personalized learning experiences and neuroscience-aided support will be developed to enhance overall learning efficiency.

## 4 Conclusions

To conclude, this paper first reviewed current studies on how phonological, orthographic, and semantic information are represented in the brains of native Chinese speakers. The visual word form area (VWFA) in the occipitotemporal cortex was identified as an important region that simultaneously represents phonological, orthographic, and semantic information during Chinese character processing.

Additionally, this paper suggests two directions for future research. One direction is to explore the dynamic changes in neural pattern similarities between native speakers and non-native Chinese learners as they reach high proficiency levels and to examine how language-related factors, such as the onset age of Chinese acquisition and cumulative exposure to Chinese, influence the neural pattern similarities. Another direction is to align large language models with human neural activity during Chinese character processing. Such alignment could greatly improve technologies related to Chinese character education for non-native learners.

## Disclosure of Interests

The author has no competing interests to declare that are relevant to the content of this article.

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