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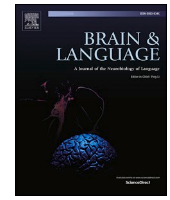

Independent syntactic representation identified in left front-temporal cortex during Chinese sentence comprehension

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ABSTRACT

It has been well established that syntactic representation is independent of semantic representation in Indo-European languages, but it is unclear whether this is the case in Chinese. The present functional magnetic resonance imaging (fMRI) study adopted a syntactic priming paradigm to investigate the neural basis of Chinese syntactic representation. A passive sentence was preceded by either a passive or an active sentence without repeating a verb or a pattern of agent-patient animacy, thus constructing primed and unprimed sentence pairs based on sentence structure. The fMRI data were collected from 22 native Chinese speakers while they were reading the sentences. Priming-related activation suppression was found in the left temporal pole, left inferior frontal gyrus and left precentral gyrus. The results are the strongest neuroimaging evidence to date that syntactic representation is independent of semantic representation in Chinese, in line with Indo-European languages.

1. Introduction

Syntactic representation in human language is an important focus of research on the neuroscience of language. Most theories of Indo-European languages assume that levels of representation such as syntax and semantics are constructed independently (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994). However, there is controversy over whether this is the case in Chinese, which has fewer explicit cues for syntactic structure.

Chinese does not morphologically mark syntactic category or syntactic features, and neither does it have a rigid word order. It contains a high proportion of words whose syntactic class is ambiguous, analogous to fight (noun) versus fight (verb) in English. Hence the syntactic role of a given word is not explicitly marked and cannot be determined until fulfilled by semantic analysis. As a consequence, the semantic dimension plays a critical role in Chinese sentence comprehension (Chen, Chen, & He, 2012; Li, Bates, & MacWhinney, 1993). This has led some researchers to conclude that syntax and semantics are intimately connected and syntactic representation is less independent from semantic representation in Chinese (Hu, 1994; Lu, 1997; Shao, 1998). Therefore, it is quite necessary to identify neural evidence of the independence of Chinese syntactic representation.

A handful of neuroimaging studies have investigated the neural basis of syntactic processing in Chinese. There is evidence of overlapping activation between syntactic processing and semantic processing in the experiment using a violation paradigm (Luke, Liu, Wai, Wan, & Tan, 2002). However, a syntactic violation related activation was found in left inferior frontal gyrus (LIFG; Wang et al., 2008). A similar independent pattern in LIFG was also found during the processing of Chinese classifier phrases (Chou, Lee, Hung, & Chen, 2012) and sentences (Feng et al., 2015; Feng, Qi, Yang, Yu, & Yang, 2020).

Unfortunately, one cannot infer the independence of syntactic representation from the results of syntactic processing studies using a violation paradigm (Huang, Pickering, Yang, Wang, & Branigan, 2016). First, it is difficult to find a sentence that is syntactically violated but semantically reasonable, especially in Chinese. Thus, the results in these earlier studies may be confounded by the semantic information, unless semantic violation was explicitly controlled in sentences with syntactic anomalies (Wang et al., 2008; Zhu, Hou, & Yang, 2018). Second, acceptability judgments of incorrect sentences could induce violation detection and automatic repair, which differs from operating syntactic representation per se (Kaan & Swaab, 2003). More critically, the above-

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mentioned studies mainly focused on language processing that operates representation online. Yet processing is different from representation. Hence, there is a need for a more appropriate paradigm to detect linguistic representation in the human brain more effectively and directly (Branigan & Pickering, 2016; Huang et al., 2016).

One mature experimental approach to investigate syntactic representation is syntactic priming (Bock, 1986; Branigan & Pickering, 2016). Given a pair of consecutive sentences, the first is called the prime, and the second is the target. The exposed structure in the prime can facilitate processing of the subsequent target with the same syntactic structure, thus aiding comprehension. According to Wiggs and Martin (1998), repeated processing of a stimulus produces a "sharpening" of its cortical representation. Neuronal coding features that are unnecessary for processing the stimulus respond less, allowing more efficient stimulus processing (Henson & Rugg, 2003). "Sharpening" results in a decrease in the mean firing rate of a population of neurons, and hence a decrease in the hemodynamic response (namely repetition suppression) from that cortical region. The syntactic priming paradigm has the advantage of being able to detect neuronal populations that are sensitive to syntactic properties shared by consecutive stimuli (Weber & Indefrey, 2009) rather than information about semantic content, lexicon and rhythm (for reviews, see Branigan & Pickering, 2016; Pickering & Ferreira, 2008). Likewise, a number of fMRI studies on Indo-European languages have revealed repetition suppression mainly in the front-temporal language network (Hasson, Nusbaum, & Small, 2006; Noppeney & Price, 2004; Segaert, Kempen, Petersson, & Hagoort, 2013).

The syntactic priming paradigm has been adopted in studies on the independence of syntactic representation in Chinese (Cai, Pickering, & Branigan, 2012; Cai, Pickering, Yan, & Branigan, 2011). In a series of experiments, Huang et al. (2016) found that participants tended to repeat syntactic structure regardless of whether verbs and semantic features were repeated across sentences, demonstrating that independent syntactic representation was computed during production. In an event-related potentials (ERPs) study on comprehension, Chen, Xu, Tan, Zhang, and Zhong (2013) found a lower P600 effect elicited by the critical Chinese word *de*[1] when the target sentence contained the same verb as the prime, compared to when the target sentence contained a synonymous verb. In contrast to Chen et al., who used a repeated verb, Wei (2017) found a lower anterior negativity in a primed target than in an unprimed target, without repeating verbs across prime and target.

Although there is behavioral and ERP evidence for the independence of syntactic representation from semantic representation, it is unclear whether this independence is registered in associated brain regions, and how these regions contribute to independent syntactic representation in Chinese. The present fMRI study adopted the priming paradigm to answer these questions. A passive sentence was preceded by either a passive or an active sentence without repeating a verb or a pattern of agent-patient animacy, thus constructing primed and unprimed sentence pairs based on sentence structure. According to previous studies, we expected to find significant repetition suppression effects in the left front-temporal language network.

2. Material and methods

2.1. Participants

College students who were native Chinese speakers ($N = 22$; 10 males; 18–25 years of age) were recruited for this experiment. They signed consent forms issued by the research ethics committee of the Institute of Linguistics at Jiangsu Normal University. All were right-handed and had normal or corrected-to-normal vision. None had a history of neurological or psychiatric disorders, or any hearing or language disorders.

2.2. Stimuli/design

Passive sentences were chosen as stimuli because this kind of sentence is the less preferred structure and allows for a more reliable detection of syntactic priming effects (Pickering & Ferreira, 2008). In addition, Chinese passive sentences also resemble passive sentences in Indo-European languages (Yang, Wu, & Zhou, 2015).

The experiment used a 2 (Sentence Type: Prime vs. Target) × 2 (Structure: Same structure vs. Different structure) design (see Table 1 for examples). There were 90 pairs of stimuli and each pair included one prime sentence and one target sentence. When the prime and the target shared the same syntactic structure, they were called the same structure prime (SP) and the same structure target (ST) respectively; when bearing different syntactic structures, they were called different structure prime (DP) and different structure target (DT) respectively. ST and DT were always the same passive sentences consisting of "patient + 被(*bei*)[2] + agent + verb + 了(*le*) [3]." In the same structure condition, SP was also a passive sentence, however it was completely different from its corresponding ST except the sentence structure. In the different structure condition, DP was an active sentence consisting of "agent + verb + 了(*le*) + patient," just structurally transformed from its corresponding SP. Hence DP and DT had different sentence structures. Importantly, neither the verb, nor the animacy of the agent and patient, overlapped across the prime and its paired target in any condition. The prime involved an inanimate patient and an animate agent, while the target involved an animate patient and an animate agent, and vice versa.

In order to avoid the difference in semantic acceptability caused by different prime sentences, 20 college students who did not participate in the fMRI scanning rated the semantic acceptability of the primes (1–5, 1 for totally unacceptable, 5 for completely acceptable). There was no significant difference (t (89) = −0.78, p = 0.44) between the acceptability of SP (M = 4.63, SD = 0.20) and DP (M = 4.65, SD = 0.23).

In addition, 90 active sentences were added as fillers to balance the frequency of active and passive sentences. Probe sentences with obvious incorrect grammar (30 active sentences and 30 passive sentences) were guised as experimental stimuli. The participants were asked to respond while reading an incorrect sentence to keep their attention from wandering. Every prime-target pair was separated by 1–2 fillers or probe sentences. The stimuli were counterbalanced across structure type and trial order. Each participant only completed one of four stimuli lists.

Table 1
Examples of experimental trials.

Structure	Prime	Target
Same structure	帽子 被 哥哥 扔掉 了。 hat *bei* elder brother throw away *le* The hat was thrown away by the elder brother.	老头 被 儿女 抛弃 了。 old man *bei* children abandon *le* The old man was abandoned by his children.
Different structure	哥哥 扔掉 了 帽子。 elder brother throw away *le* hat The elder brother threw the hat away.	老头 被 儿女 抛弃 了。 old man *bei* children abandon *le* The old man was abandoned by his children.

[1] In Chinese, the word *de(的)* serves as a relative clause marker. When reading, Chinese readers initially expect a Subject-Verb-Object (SVO) structure, but if they encounter the relative clause marker *de* they abandon the initial strategy and re-analyze the structure as a relative clause (Chen et al., 2013).

[2] In Chinese, 被(*bei*) is a preposition indicating passivity.

[3] In Chinese, 了(*le*) is an auxiliary indicating the completion of an action.

2.3. Procedure

The main fMRI experiment involved 90 pairs of experimental sentences, 90 filler sentences and 60 probe sentences. The experiment was divided into four runs, with a short break interval. There was a 4 s dummy scan at the beginning of each run. On each trial, a 400 ms fixation cross was followed by a 100 ms blank screen. Next, each sentence was presented for 2 s during which the participant needed to press the button box as soon as possible in response to an incorrect sentence. If the reaction time (RT) was<2 s, a following blank screen was presented to ensure that the total duration of each trial remained the same. In order to ensure the purity of the priming effect, the prime and the target were independent of each other. Based on a self-paced pre-test reading task, the random inter-stimulus interval (ISI) between the prime and target was jittered 0.5 s, 2 s, and 2.5 s, and the random ISI between other sentences was jittered 0.5 s to 3.5 s by a step of 0.5 s, with a total average ISI of 2 s.

2.4. fMRI data acquisition

The fMRI data were acquired on a GE-MR750 3 T system in the Jiangsu Key Laboratory of Language and Cognitive Neuroscience, using a T2*-weighted echo planar imaging sequence, with 2 s repetition time, 35 ms echo time, and 90° flip angle. We acquired 35 slices with a voxel size of 3.5 × 3.5 × 3.5 mm. The field of view was 224 × 224 mm for each slice. The slices were acquired in an interleaved manner in ascending order. Head motion was minimized using pillows and cushions around the head and forehead strap.

2.5. fMRI data preprocessing

The fMRI data were preprocessed and analyzed by the FEAT tool (Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004) in FSL v5.0 (Functional MRI of the Brain software library, FMRIB) using the Linux operating system (CentOS 6.5). The data format was converted using the MRICroN Dcm2nii tool (http://www.mccauslandcenter.sc.edu/mricro/mricron/), and the data of the first two scans were discarded to reduce the impact of machine preheating on data when starting up. Acquisition time correction, head movement correction, high-pass filtering to 128 Hz and spatial smoothing (FWHM = 8 mm) were carried out on the data in turn.

2.6. Whole-brain analysis

In individual analysis, we performed a general linear model that included four types of sentences (SP, ST, DP, DT), three types of fillers (correct filler, incorrect active sentence and incorrect passive sentence), incorrect responses and six head motion parameters obtained by head motion correction. The onset time was the starting time of each sentence, and the duration was the RT. A canonical hemodynamic response function (HRF) was performed to fit the model. After the individual data was normalized to MNI space, the mixed effects model was used to perform group analysis with participants as random effects variables and conditions as fixed effects variables. Following previous studies (Kim, Johnson, Cilles, & Gold, 2011; Zhu et al., 2012), we defined the activation for each sentence by contrasting the sentence versus fixation. We performed a voxel-wise 2 (Structure: Same structure, Different structure) × 2 (Sentence Type: Prime, Target) multivariate analysis of variance (ANOVAs) at group level. A corrected p of 0.05 was determined using AlphaSim simulation, based on an uncorrected p value below 0.001 and a cluster size of no<60 voxels.

2.7. Region of interest (ROI) analysis

Since a weak activation pattern was found in the whole-brain analysis, we performed a region of interest (ROI) analysis which is considered at the highest possible statistical sensitivity in detecting syntactic repetition suppression effects (Weber & Indefrey, 2009). The common brain regions activated by both SP and DP were selected as the ROIs, namely LIFG, left precentral gyrus (LpreCG), left temporal pole (LTP) and left posterior superior temporal gyrus (LpSTG), which survived in the correction for multiple comparisons at $p = 0.05$ according to AlphaSim simulation and were regions related to syntax in the previous reviews (Friederici, 2011; Hagoort, 2013). Signals for all ROIs were extracted by drawing a 6 mm sphere with the peak voxel as the center. To avoid the double-dipping risk, only signal of the target sentences (DT vs. ST) was compared via paired samples t-tests with IBM SPSS (version 21).

3. Results

RT and accuracy on the probes were mainly used to evaluate whether participants had concentrated on the experiment. The average accuracy ($M = 92\%$, $SD = 2$) and RT ($M = 1621$ ms, $SD = 363$) indicated that all participants could effectively complete the task.

For each condition in whole-brain analysis, significant activations were found in the front-temporal language network (Fig. 1), including LIFG, bilateral anterior temporal gyri, posterior middle and superior temporal gyri, precentral and postcentral gyri, and occipital-temporal gyri. For whole-brain analysis, no significant results for main effects or interaction were found in the 2 × 2 examination at corrected $p = 0.05$ level.

ROI analysis results (Fig. 2) showed that the activation intensity of ST was lower than that of DT in the LIFG (Fig. 2B; $t\,(21) = -2.31$, $p < 0.05$), the LpreCG (Fig. 2C; $t\,(21) = -3.32$, $p < 0.01$) and the LTP (Fig. 2D; $t\,(21) = -3.19$, $p < 0.01$), but not the LpSTG (Fig. 2E; $t\,(21) = -1.44$, $p = 0.17$).

4. Discussion

The present fMRI study adopted the syntactic priming paradigm to reveal neural associates with syntactic representation in Chinese. ROI analyses detected significant repetition suppression effects in the front-temporal language network, specifically LTP, LIFG, and LpreCG. The results provide the strongest neuroimaging evidence to date that as in Indo-European languages, syntactic representation is independent of semantic representation in Chinese.

The syntactic priming effects identified here cannot be explained by verb repetition. Some previous studies showed that there is a significant syntactic priming effect only when the verb is repeated (Carminati, van Gompel, Scheepers, & Arai, 2008; Chen et al., 2013; Ledoux, Traxler, & Swaab, 2007; Tooley, Traxler, & Swaab, 2009). However, the fact that we observed significant priming effects without a repeating verb clearly demonstrates that syntactic priming is due to the facilitation of syntactic structure, not verb repetition. These results are consistent with those of previous studies (Ivanova, Pickering, Branigan, McLean, & Costa, 2012; Thothathiri & Snedeker, 2008a, b; Traxler, 2008). To reconcile the present study with those that found facilitation due to verb repetition, one could assume a separate neural basis for lexical and structural priming. This is exactly what was found by Tooley and Traxler (2018) and Segaert et al. (2013).

Furthermore, the syntactic priming effects found here were not due to animacy information. Animacy plays an important role in Chinese sentence processing (e.g., Li et al., 1993; Philipp, Bornkessel-Schlesewsky, Bisang, & Schlesewsky, 2008; Yang & Liu, 2014). In Wei (2017), the animacy dimension of nouns across the prime and target was not well controlled, and the representation revealed by the priming effect might have been due to an integration of syntactic and semantic information. In the current study, however, the animacy of the agent-patient did not overlap in the prime-target sentence pairs, eliminating the confounding effect of animacy. The results support the assumption that the processing of Chinese involves the computation of autonomous

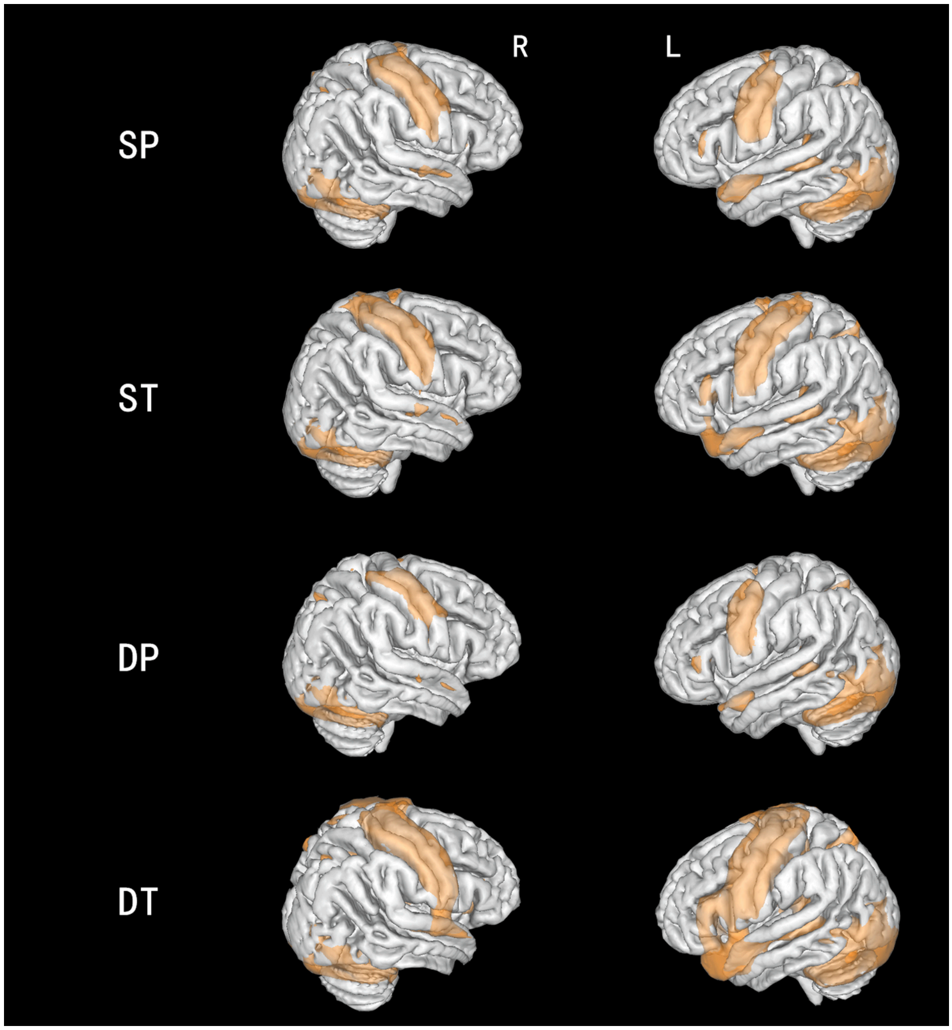

Fig. 1. Brain activation for prime and target sentences. SP and ST for the prime and the target in the same structure condition respectively; DP and DT for the prime and the target in the different structure condition respectively. Corrected p at 0.05 level. L for left and R for right.

syntactic representation, in accordance with recent evidence of cortical tracking of hierarchical linguistic structures in connected speech (Ding, Melloni, Zhang, Tian, & Poeppel, 2016). Interestingly, Zhang et al. (2013) found that semantic integration is independent of the syntactic construction in Chinese sentence comprehension. Combined with the current results, one may infer that different levels of representation in Chinese, such as syntax and semantics, are constructed independently.

Importantly, this experiment provides neural evidence of independent Chinese syntactic representation, hence extending previous behavioral and ERP studies on syntactic priming (Cai et al., 2012; Cai et al., 2011; Chen et al., 2013; Huang et al., 2016; Wei, 2017) to the localization in cerebral cortex. The repetition suppression effects in LTP, LIFG, and LpreCG regions indicated that neuronal populations here underpin syntactic representation that is shared by consecutive sentences. The purpose of sentence comprehension is to construct the structure “who is doing what to whom.” Once the sentence structure is established, it is stored in working memory unless an update is required. In the present study, the structural template of the prime could have been reactivated unconsciously and immediately projected onto the target sentence, activating the argument structure corresponding to the previous one in working memory. Thus, it would be easier to process the target and there would be less demand on brain resources. By contrast, if structures are different across the prime and target sentences, the previous argument structure will be abandoned, and then it is necessary to construct a new argument structure. In a word, as the number of shared syntactic representations between the prime and target increases, the activation of the neuron populations responsible for these representations decreases accordingly. This pattern was documented in Wei’s ERP experiments, where a decreased anterior negativity wave was found (Wei, 2017).

As noted by Noppeney and Price (2004), the LTP may be related to the process of building up an initial phrase structure (for a review, see Friederici, 2011). Since ST and DT were all passive sentences, the LIFG may be related to the syntactic movement of the object in the passive sentence (Ben-Shachar, Palti, & Grodzinsky, 2004; Feng et al., 2015). According to the Memory, Unification and Control (MUC) model (Hagoort, 2013), syntactic integration involves not only the LIFG but also part of the precentral gyrus. The LpreCG may have a facilitation effect in the structural coding process, as was documented in previous priming studies (Segaert et al., 2013; Weber & Indefrey, 2009). The LpSTG aids the interpretation of natural sentences but not sentences using artificial grammar where no semantic information is available (Friederici, 2011). Thus, this area integrates syntactic and thematic information. In this experiment, neither animacy features nor verbs overlapped across the prime and target sentences. This required the thematic role in consecutive stimuli to be assigned anew. As a consequence, no repetitive suppression effect was detected in the LpSTG, although this region was activated under all four conditions. In this experiment, the prime and the target were independent of each other, and there was no favorable bias to induce priming effect deliberately,

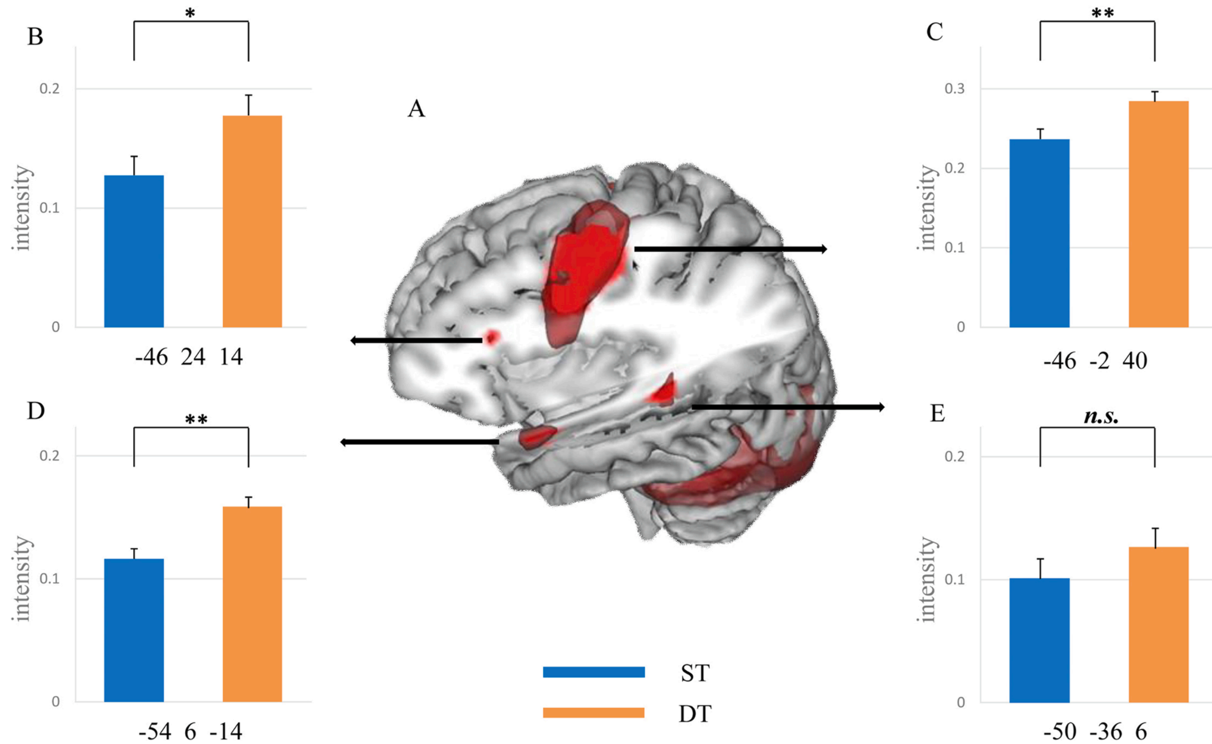

Fig. 2. Mean activation intensities (standard error) for ST and DT in the four ROIs in the left hemisphere. (A) shows four ROIs that were identified in the common brain regions activated by both SP and DP. The activation intensity of ST was significantly lower than that of DT in the LIFG (B), LpreCG (C), and LTP (D), thus showing repetition suppression effects. However, there was no difference between ST and DT in LpSTG (E). ST for the target in the same structure condition, and DT for the target in the different structure condition. The MNI coordinates are presented for each ROI. ** $p < 0.01$, * $p < 0.05$, *n.s.* nonsignificant.

which ensured that the priming effect was pure, but at the expense of the strength of priming effect.

In conclusion, with few inflectional morphology markers in Chinese, the syntactic role of a given word heavily depends on semantic analysis. However, there has been no clear evidence of which brain regions are associated with independent syntactic representation. By employing a syntactic priming paradigm, which provides evidence that is directly informative about mental representation, the present study found syntactic repetition suppression effects in the LTP, LIFG and LpreCG. The results are the strongest neuroimaging evidence to date that syntactic representation is independent of semantic representation in Chinese, in line with Indo-European languages. Therefore, it also solves long-standing theoretical disputes. Moreover, the successful use of the syntactic priming paradigm in this fMRI study also indicates that this method can be useful in future related research.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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