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RESEARCH ARTICLE

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The depth of semantic processing modulates cross-language pattern similarity in Chinese–English bilinguals

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Abstract

Previous studies have investigated factors related to the degree of cross-language overlap in brain activations in bilinguals/multilinguals. However, it is still unclear whether and how the depth of semantic processing (a critical task-related factor) affects the neural pattern similarity between native and second languages. To address this question, 26 Chinese–English bilinguals were scanned with fMRI while performing a word naming task (i.e., a task with shallow semantic processing) and a semantic judgment task (i.e., a task with deep semantic processing) in both native and second languages. Based on three sets of representational similarity analysis (whole brain, ROI-based, and within-language vs. cross-language semantic representation), we found that select regions in the reading brain network showed higher cross-language pattern similarity and higher cross-language semantic representations during deep semantic processing than during shallow semantic processing. These results suggest that compared to shallow semantic processing, deep semantic processing may lead to greater language-independent processing (i.e., cross-language semantic representation) and cross-language pattern similarity, and provide direct quantitative neuroimaging evidence for cognitive models of bilingual lexical memory.

KEYWORDS
bilingual, fMRI, lexical memory, Reading, the depth of semantic processing

1 | INTRODUCTION

How the native and second languages are represented in the brain has been a topic of interest to researchers for some time (Illes et al., 1999; Li et al., 2019; Ou et al., 2020; Qu et al., 2019; Xu et al., 2017). By comparing neural activity elicited by different languages in bilinguals or multilinguals, existing research has revealed that native and second languages have common activations in a wide neural network, including the prefrontal cortex, temporoparietal regions, and occipitotemporal regions (Cao et al., 2013; Chee et al., 1999; Dong et al., 2020; Feng et al., 2020; Klein et al., 1995; Li et al., 2019; Nichols et al., 2021; Ou et al., 2020; Wang et al., 2011; Wong et al., 2016; Xue et al., 2004; Yokoyama et al., 2006). Subsequent studies further revealed that linguistic factors (e.g., language distance between native and second languages) and learner-related factors (e.g., proficiency and age of acquisition in the second language) modulated the degree of similarity in activation patterns between native and second languages (Berken et al., 2015; Bloch et al., 2009;

Huiling Li and Ying Cao contributed equally to this work.

Cargnelutti et al., 2019; Li et al., 2021; Liu & Cao, 2016; Nichols et al., 2021; Xu et al., 2021). For example, compared to late bilinguals or bilinguals with lower second language proficiency, early bilinguals or bilinguals with higher proficiency in the second language showed less activation differences between the two languages (Chee et al., 2001; Gao et al., 2017; Lee et al., 2003; Sebastian et al., 2011; Wartenburger et al., 2003; Xu et al., 2021).

In addition to the above-mentioned factors, task-related factors may also influence cross-language similarity in neural activations. One major task-related factor is its differential reliance on the various linguistic components (e.g., orthography, phonology, and semantics) (Ding et al., 2003; Indefrey, 2006; Mano et al., 2013; Qu et al., 2022; Sulpizio et al., 2020). For example, passive viewing, rhyming, and semantic judgment tasks should primarily tap orthographic, phonological, and semantic processing, respectively. Previous studies have examined how these linguistic components are represented in bilinguals. Such research has led to the Revised Hierarchical Model, which proposes that the native and second languages share semantic representations but have distinct orthographic and phonological representations (Kroll & Stewart, 1994; Kroll & Tokowicz, 2005). According to this model, bilinguals would show more similar representations in the semantic task relative to tasks that rely primarily on orthographic or phonological processing. In support of the shared semantic representations, previous behavioral research found substantial cross-language semantic priming effects in Spanish-English bilinguals (Francis & Goldmann, 2011; Taylor & Francis, 2017) and Chinese–English bilinguals (Chen et al., 2014; Meng et al., 2016). In contrast, because of the distinct lexical and phonological representations, the cross-language priming effect was much weaker in a lexical decision task (Li et al., 2009; Zeelenberg et al., 2003) or a word-naming task (Kim & Davis, 2003).

The Revised Hierarchical Model has also received support from neuroimaging studies. Semantic tasks elicit common activations for native and second languages (Ding et al., 2003; Li et al., 2019; Xue et al., 2004), whereas non-semantic tasks (e.g., orthographic and phonological processing) elicit distinct activations for the two languages (Jamal et al., 2012; Liu et al., 2010; Tham et al., 2005). A recent meta-analysis drew the conclusion of vast activation differences between native and second languages in extensive clusters within the bilateral frontal, temporal, and occipital regions during orthographic and phonological processing, but mostly similar activation patterns between the two languages during semantic processing (with evident cross-language differences only in three clusters within the temporal lobe and precentral gyrus) (Comstock & Oliver, 2021).

Although previous studies indicate that the neural organization of native and second languages may depend on the depth of semantic processing (i.e., deep vs, shallow semantic processing), they had at least three limitations. First, little research has directly compared cross-language similarity in activation patterns across different tasks with different depth of semantic processing (e.g., the semantic judgment task vs. the word naming task), and consequently direct evidence is needed for the effect of semantic processing depth on cross-language pattern similarity. Second, previous studies were limited to the use of traditional univariate analysis to examine overlapping and distinct activations between the two languages (Kuper et al., 2021; Pillai et al., 2003). Such an approach focuses on the mean level of activity across a population of voxels and fails to consider multi-voxel pattern information (Dimsdale-Zucker & Ranganath, 2018; Haxby, 2012; Haynes, 2015). The multi-voxel pattern information should be taken into account because there is evidence that the neural pattern information is more sensitive than mean activation across voxels in detecting neural similarity between conditions (Carlos et al., 2019; Li et al., 2019; Xu et al., 2017) and because the neural pattern information has been repeatedly found to be associated with information processing (Haxby, 2012; Haynes, 2015; Heilbron et al., 2020; Norman et al., 2006). Consistently, multivariate methods (e.g., representational similarity analysis, RSA), which compute multi-voxel pattern information (Dimsdale-Zucker & Ranganath, 2018; Haxby, 2012; Haynes, 2015), can be used to reliably estimate neural pattern similarity between native and second languages and specify brain regions showing differences in cross-language pattern similarity across different conditions (Dong et al., 2021; Li et al., 2019; Qu et al., 2019). Finally, far less attention has been paid to whether differences in cross-language pattern similarity across tasks are driven by semantic processing. The use of RSA would help to address this question by associating neural pattern information with semantic prediction matrix. In addition, another advantage of RSA is that it can be used to explore within-language vs. cross-language semantic representations by examining within-language and cross-language associations between neural pattern information and semantic prediction matrix, respectively. It has been revealed that, compared to within-language semantic representations involving language-specific information, cross-language information processing is more dependent on language-independent semantic properties in bilinguals (Correia et al., 2014; Correia et al., 2015; Phillips et al., 2006). Consistently, by using RSA, previous studies have identified within-language and cross-language semantic representations in sign-speech bilinguals, and found that cross-language semantic representations reflect common semantic representations between languages (Evans et al., 2019). Therefore, RSA is needed to disentangle the associations between activation patterns and within-language/cross-language semantic representations.

In the current study, we focused on the question of whether and how the depth of semantic processing affected cross-language similarity in neural representations. We used two tasks: a word naming task and a semantic judgment task. The semantic judgment task requires mentally simulating the properties associated with the word concept, which is more likely to promote deep semantic access. In contrast, although the semantic processing has been identified as a stage of activity during word naming (Forseth et al., 2018; Indefrey & Levelt, 2004), rich semantic analyses are not mandatory in the naming task. Because the two tasks differed in the extent of semantic processing, we use the term of “depth of semantic processing” to differentiate the main process involved in those tasks. Twenty-six Chinese–English bilinguals completed the two tasks while being scanned with fMRI. Both whole-brain RSA and ROI-based RSA were used to examine task differences in cross-language pattern similarity. Within the brain regions that showed significant task differences, we further examined within-language and cross-language semantic representations by correlating neural representation dissimilarity matrix with semantic prediction matrix (i.e., dissimilarities [or distance] among the words in terms of semantic features). Orthographic and phonological prediction matrices were additionally constructed and controlled to rule out the possibility that any task effects had been driven by such nonsemantic information. The contributions of the within-language and cross-language semantic representations to cross-language pattern similarity were further examined by direct comparison between the two tasks in within- and cross-language semantic representations. We hypothesized that, compared with the shallow semantic processing condition, the deep semantic processing condition would induce greater cross-language pattern similarity by enhancing cross-language semantic representation.

2 | METHODS

2.1 | Participants

Twenty-six unbalanced Chinese–English bilinguals (13 males) were recruited for this study. They were 18–25 years of age and right-handed. They had normal or corrected-to-normal vision, and reported no history of neurological or language learning impairments. They all had learned English as a second language for about 12 years. Their self-reported English proficiency on a 7-point scale (1 poor—7 excellent) was moderate: 4.08 (SD = 0.80) in reading, 3.85 (SD = 0.67) in writing, 3.65 (SD = 0.80) in listening, and 3.38 (SD = 0.98) in speaking. All participants provided written informed consent before participation and this study was approved by Institutional Review Board of the School of Psychology at South China Normal University.

3 | MATERIALS

Stimuli were selected from previous studies (Cai & Brysbaert, 2010; Chen et al., 2014), and consisted of 60 Chinese two-character words (mean number of strokes = 16.98 ± 5.28) and their English translations (mean number of letters = 5.87 ± 1.83). These words belong to two categories: concrete and abstract. Concrete words consisted of five subcategories including clothes, body parts, animals, parts of buildings, and fruits. Similarly, abstract words consisted of five subcategories including time units, physical units, diseases, scientific disciplines, and subfields of art. Each subcategory consisted of six words. All Chinese words (mean = 42.48 per million, SD = 68.33) and English words (mean = 47.03 per million, SD = 63.26) were medium- to high-frequency. To ensure that the semantics were consistent across words in the native and second languages (e.g. 脖子[neck]—neck), an additional group of 20 Chinese–English bilingual students were recruited to translate the words. Half of these students were asked to translate Chinese words into English, and the other half were asked to translate English words into Chinese. For each word, the translation equivalent was correctly provided by at least seven out of the 10 raters in each group, indicating that all Chinese–English word pairs were semantically equivalent word pairs. Furthermore, in order to ensure that the participants were familiar with the words, a separate group of 10 participants with comparable proficiency in English were asked to evaluate word familiarity on a 7-point scale (1 = "very unfamiliar," 7 = "very familiar"). The mean ratings were 6.97 (SD = 0.07) for Chinese words and 6.83 (SD = 0.38) for English words, suggesting that the materials should be familiar to the participants.

4 | PROCEDURE

Before scanning, each participant was trained on all tasks using a separate set of stimuli. During both the practice of word naming and sematic judgment tasks, participants were instructed to respond as fast as possible, while keeping their body and head as still as possible, and their eyes open and fixated on a cross in the middle of the display screen.

During fMRI scanning, participants were asked to complete both a word naming task and a semantic judgment task (Figure 1a). The order of tasks was counter-balanced across participants. For both tasks, a slow event-related design was used to precisely estimate the neural responses of single trials. Both tasks consisted of 2 runs. Each run contained 15 trials for each of the four conditions (i.e., Chinese concrete words, Chinese abstract words, English concrete words, and English abstract words). In each trial, a fixation was presented for 1 s, followed by a word displayed for 3 s. In the naming task, participants were instructed to overtly read the word as quickly and correctly as possible. Due to the high noise in the scanning process, the behavioral responses of the naming task were recorded after scanning. In the semantic judgment task, participants were asked to judge whether the word was concrete or abstract by pressing one of two keys. Each word occurred once per run. Once the word disappeared, participants were asked to complete a self-paced perceptual orientation judgment task for 8 s. This task was used to prevent participants from further rehearsing the word and to make this task very engaging (Qu et al., 2021; Xue et al., 2010; Xue et al., 2013; Zhao et al., 2017). In this task, a Gabor image tilting 45° to the left or the right was randomly presented, and participants were asked to judge the orientation of the Gabor as quickly and accurately as possible.

4.1 | MRI scanning protocols

Functional and structural MRI scans were acquired on a Siemens 3T scanner at the MRI Center at South China Normal University. Specifically, for each individual, functional images of the two tasks were collected using the same T2-weighted gradient echo planar imaging sequence with the following parameters: repetition time = 2000 ms, echo time = 30 ms, flip angle = 90°, field of view = 224 × 224 mm,

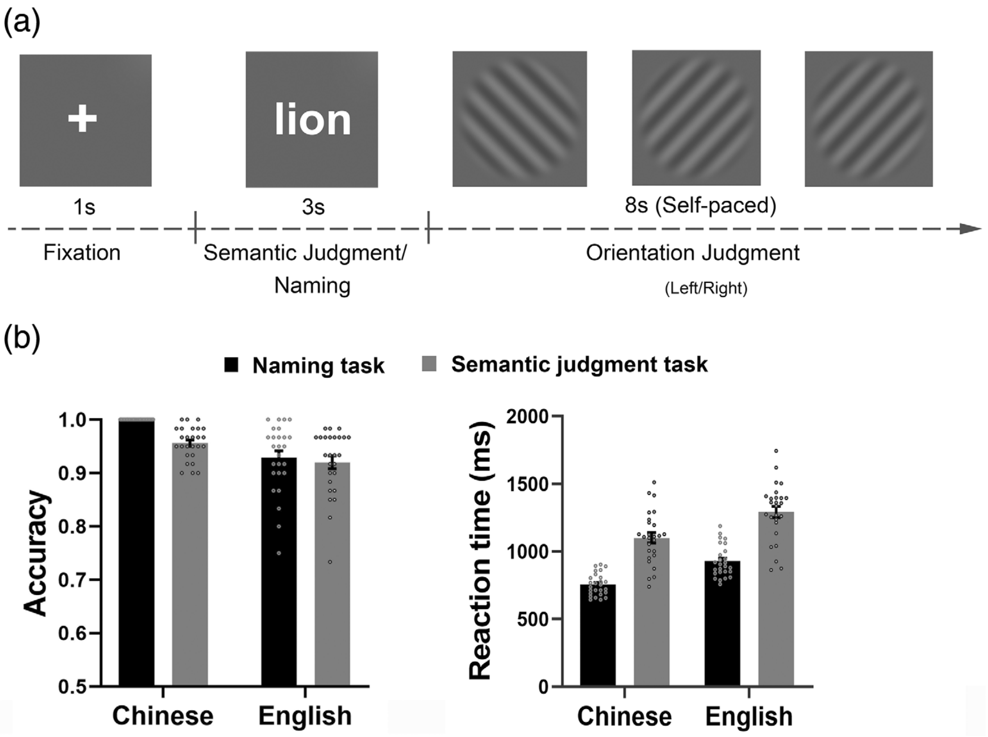

FIGURE 1 The fMRI task (a) and behavioral performance (b). Error bars represent the standard error of the mean and all scatter points represent individual data points

image matrix = 64 × 64, voxel size = 3.5 × 3.5 × 4.4 mm^3. Thirty-two contiguous axial slices (thickness = 3.5 mm) were obtained to provide full coverage of the brain. High-resolution structural images were collected using a T1-weighted, MPRAGE sequence. The specific scanning parameters were: repetition time = 1900 ms, echo time = 2.52 ms, flip angle = 9°, field of view = 256 × 256 mm, image matrix = 256 × 256, number of slices = 176, slice thickness = 1 mm, and voxel size = 1 × 1 × 1 mm^3.

5 | MRI DATA ANALYSIS

5.1 | Preprocessing of fMRI data

MRI data were preprocessed using FEAT (FMRI Expert Analysis Tool) Version 6.00, part of FSL (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl). The first four functional images of each run were discarded to ensure stability of the MR signal. The remaining functional images were then motion-corrected using MCFLIRT (Jenkinson et al., 2002), and stripped of non-brain tissue using the brain extraction tool (Smith, 2002). The six motion parameters (i.e., three translation and three rotation parameters) were no more than 3 mm of displacement or 3 degrees of rotation in any direction for any subject or run. These parameters were also used to calculate an overall estimate of motion—the framewise displacement (FD), defined as the sum of the absolute temporal derivatives of the six motion parameters, following conversion of rotational parameters to distances by computing the arc length displacement on the surface of a sphere with radius 50 mm (Power et al., 2012). Direct comparison revealed that there was no significant difference in FD between the naming and semantic tasks ($p = .991$).

Next, all imaging data were temporally filtered by using a nonlinear high-pass filter with a 100-s cutoff. They were then registered to standard Montreal Neurological Institute (MNI) space using a two-step registration from functional images to high resolution structural images and to MNI-template (Jenkinson & Smith, 2001). Registration from high resolution structural image to standard MNI space was further refined using FNIRT nonlinear registration (Andersson et al., 2007a, 2007b). For univariate analysis, the functional images were spatially smoothed using a Gaussian kernel of 5 mm full-width-half-maximum (FWHM). For representational similarity analysis, no spatial smoothing was applied.

5.2 | Analysis of brain activation

To test differences in whole-brain activation amplitude between Chinese and English words, we performed a univariate analysis. First, a general linear model was applied to model each participant's preprocessed data for each task within a run. The onsets and durations of the words were convolved with the double-gamma hemodynamic response function (HRF) to generate the regressors used in the GLM. To minimize the effects of motion artifacts, six motion parameters and temporal derivatives were additionally included as covariates of no interest. The orientation judgment task and fixation served as baseline. Four contrast images (Chinese words > baseline, English words > baseline, Chinese words > English words, and English words > Chinese words) were computed separately for each task within each run. Then, for each participant, a fixed-effects model was performed to get the averaged activation across the two runs of each task. Finally, a random-effects model was used to obtain group activation. Unless otherwise stated, all reported group images were thresholded using clusters determined by $Z > 2.6$ and a cluster probability of $p < .05$, corrected for whole-brain multiple comparisons using the Gaussian random field theory (Worsley, 2000).

5.3 | Representational similarity analysis

Three sets of multivariate representational similarity analyses (RSA) were performed in this study. The first two sets of RSA (whole-based and ROI-based RSA) were used to quantify cross-language neural pattern similarity by computing correlations between native and second languages on multi-voxel activation patterns. We first obtained trial-level neural response patterns (i.e., beta maps) by modeling the unsmoothed native-space functional images for each run of each task. In this model, each word presented in each language was modeled as a separate regressor and convolved with a canonical double-gamma hemodynamic response function. After model estimation, the beta map associated with each word was obtained using ordinary least squares estimation as well as ridge regression (Li et al., 2019; Xue et al., 2010; Ye et al., 2016) and was normalized to the MNI space (Wang, Xu, et al., 2018). These response patterns were used in the subsequent searchlight-based RSA and region-of-interest-based (ROI-based) RSA.

In the whole-brain searchlight-based RSA, we used a voxel-wise searchlight approach with the following procedures (Figure S1A). First, for each participant, a spherical searchlight with 5 mm radius was moved throughout the grey matter to extract the word-elicited activation patterns within each run for each task (Chyl et al., 2021). The grey matter mask was generated from AAL template. For each searchlight, Spearman rank correlation coefficients were calculated between the activation patterns of Chinese words and those of their English equivalents (e.g., 脖子[neck]—neck, 香蕉[banana]—banana). We also calculated Spearman rank correlation coefficients between the activation patterns of Chinese words and those of semantically unrelated English words (e.g., 脖子[neck]—banana, 香蕉[banana]—neck). These correlation coefficients were transformed into Fisher's *z*-scores. To rule out the possibility that a significant difference between the shallow and deep semantic processing conditions was driven by irrelevant variables (e.g., motoric demands), item-specific cross-language neural pattern similarity was then calculated by subtracting the mean z-scores of the semantically unrelated word pairs from those of semantically equivalent word pairs. Such a subtraction should have greatly eliminated the potential confounding effect of different motoric demands between the semantic judgment and word naming tasks. This item-specific similarity score was mapped back upon the searchlight's center voxel, yielding a whole-brain map showing cross-language pattern similarity. Next, the brain maps of the two runs of each task were averaged for each participant. At the same time, the contrast map between cross-language pattern similarity of the naming task and that of the semantic task was constructed for each participant. Finally, participants' brain maps were subjected to group analysis using a random-effects model. The threshold for the searchlight analysis was the same as the activation analysis described above.

In the ROI-based RSA, we defined 12 brain regions as ROIs, including the precuneus and left pars triangularis, pars opercularis, orbitofrontal cortex, anterior temporal lobe, superior temporal gyrus, middle temporal gyrus, inferior temporal gyrus, fusiform gyrus, supramarginal gyrus, angular gyrus, and superior parietal lobule. All these regions have been repeatedly reported in the previous reading studies (Binder et al., 2009; Feng et al., 2020; Liuzzi et al., 2019) and were defined based on the Harvard-Oxford probabilistic atlas (Maximal Probability Threshold: 25%) within FSL (see Table S1). Then, following previous research (Taylor et al., 2019), we extracted mean cross-language correlation values in those ROIs from whole-brain searchlight maps for each participant. Finally, to avoid inflated false positive rates in statistical inference, a nonparametric paired-sample permutation test (Millard, 2013) was used to determine the significance level of task differences in cross-language correlation values. The permutation was repeated 10,000 times, and a 95% confidence interval was used.

Finally, in the third set of RSA, we examined whether within-language and cross-language semantic representations in brain regions identified above differed between the two tasks (i.e., the naming and semantic tasks) (Figure S1B). In this analysis, we correlated neural representational dissimilarity matrices (nRDMs) with semantic prediction matrix. Note that orthographic and phonological prediction matrices were additionally constructed for further analyses to rule out the possibility that any task effects may be driven by such non-semantic information. For each run within each task, we first extracted voxel-wise response patterns in a given ROI to each word. Next, by using the correlation distances (1—Spearman's correlation), dissimilarities in response patterns between every pair of words were estimated separately for Chinese words and English words. This step resulted in two 30 × 30 nRDMs (i.e., Chinese and English nRDMs) for each run within each task.

A within-language semantic prediction matrix was constructed for each run within each task. Word pairs from the same semantic category had a dissimilarity coefficient of 0, whereas pairs from different categories had a dissimilarity coefficient of 1. Two control stimulus-feature prediction matrices were constructed in the following way. For the visual prediction matrix, the image (175 × 175 pixels) of each word was converted to binary silhouette images, in which all background pixels had the value 0 and all figure pixels had the value 1. The binary silhouette of each word was then used to compute the pixel-wise nonoverlap regions between all image pairs in each language (Dong et al., 2020; Fischer-Baum et al., 2017; Kriegeskorte et al., 2008). The phonological prediction matrix for Chinese words was based on Chinese pinyin system. Phonological representation was estimated by using 63 sub-syllabic units, including 23 onsets, 34 finals, 5 tones, and 1 unit to represent null onsets (Perfetti et al., 2005). The phonological dissimilarity between a pair of Chinese words was computed by one minus Spearman correlation. For English words, phonological match values between words were estimated by the N-Watch program developed by Davis (2005). A match value is a value between 0 and 1 that represents the match between two letter strings, where 0 indicates no match and 1 indicates a perfect match. Thus, the phonological dissimilarity matrix was computed as 1 minus the match value between two English words. In accordance with nRDMs, for each stimulus-feature prediction matrix, there were two 30 × 30 dissimilarity matrices (i.e., Chinese and English RDMs) for each run within each task.

For each run within each task, nRDMs were then correlated with the semantic prediction matrices by using Spearman rank correlation, separately for Chinese words and English words. Partial correlations were also performed to control for visual and phonological dissimilarity matrices. Next, these correlation coefficients of Chinese and English words were transformed into Fisher's *z*-scores and averaged to obtain within-language correlations. Finally, these within-language correlations were submitted to a nonparametric one-sample permutation test to identify ROIs in which the correlation was greater than zero. A nonparametric paired-sample permutation test was also used to test for significant differences in within-language correlations between the naming and semantic tasks. Both permutations were repeated 10,000 times, and a 95% confidence interval was used.

In addition to within-language information representation within the ROIs mentioned above, we further explored relationship between cross-language nRDMs and cross-language semantic prediction matrix to examine task effect on cross-language semantic representation. In this analysis, as mentioned above, activation patterns in a given ROI to each word were extracted for each run within each task. Next, for each ROI, the neural dissimilarity was computed by 1 minus Spearman correlation for activation patterns of each cross-language word pair, resulting in a 30 × 30 cross-language nRDM. Then, the cross-language semantic prediction matrix was estimated according to their similarity in semantic category. Specifically, cross-language word pairs from the same semantic category were denoted as 0, and those from different categories were denoted as 1 (Figure S1B). Finally, we computed a Spearman correlation between the nRDM and semantic prediction matrix. These correlation coefficients were transformed into Fisher's z-scores and compared between two tasks. Permutation tests were conducted to determine the significance level of the Fisher-transformed correlation coefficients. The permutation procedure was the same as that in the within-language RSA.

6 | RESULTS

6.1 | Behavioral performance

A two-way repeated-measures ANOVA on accuracy revealed a significant main effect of language ($F_{1,25} = 28.58$, $p < .001$), a significant main effect of task ($F_{1,25} = 12.22$, $p < .001$), and a significant language-by-task interaction ($F_{1,25} = 5.98$, $p = .022$) (Figure 1b). Simple effects analysis revealed that accuracy was higher for Chinese words than English words in both tasks (*ps* <0.01), and higher for word naming than semantic judgment in Chinese ($F_{1,25} = 53.30$, $p < .001$), but not in English ($F_{1,25} = 0.44$, $p = .513$). In terms of reaction time, the main effects of language ($F_{1,25} = 162.62$, $p < .001$) and task ($F_{1,25} = 64.03$, $p < .001$) were significant. Specifically, the reaction time of Chinese words was shorter than that of English words in both tasks (Naming: $F_{1,25} = 77.95$, $p < .001$, Semantic: $F_{1,25} = 184.12$, $p < .001$), and the reaction time in the naming task was shorter than that in the semantic task in both languages (Chinese: $F_{1,25} = 61.19$, $p < .001$, English: $F_{1,25} = 61.57$, $p < .001$). The effect of language-by-task interaction was not significant ($F_{1,25} = 1.12$, $p = .300$). These results confirmed that participants in this study were unbalanced bilinguals, being more proficient in Chinese than in English.

6.2 | Brain activations for Chinese and English words

Univariate analyses revealed that, for both the naming and semantic tasks (Figure 2), Chinese and English words yielded extensive activations in the typical reading-related regions, including the bilateral prefrontal cortex, occipitotemporal cortex, and occipitoparietal cortex (Dong et al., 2020; Feng et al., 2020; Li et al., 2019; Liuzzi et al., 2019). Direct comparisons between the two languages revealed significant differences in certain regions. For the naming task, Chinese words elicited greater activation in the bilateral middle frontal gyrus, middle temporal gyrus, angular gyrus, and lateral occipital cortex, whereas English words elicited greater activation in the bilateral insula, superior parietal lobule, left precentral gyrus, inferior frontal gyrus, and inferior temporal gyrus. For the semantic task, Chinese words elicited greater activation in the left angular gyrus and right occipital cortex, whereas English words elicited greater activation in the bilateral insula, superior parietal lobule, left precentral gyrus, inferior frontal gyrus, and inferior temporal gyrus. Similar brain regions were found when a more stringent threshold (voxel level at $p < .001$; cluster-extent FWE $p < .05$) was adopted in the activation analysis (Figure S2).

6.3 | The depth of semantic processing modulated Cross-Language pattern similarity

We then quantitatively examined task differences in neural pattern similarity between Chinese and English words by using RSA. For both naming and semantic tasks, the searchlight-based RSA revealed significant cross-language pattern similarity in the precuneus, bilateral prefrontal cortex, lateral temporal cortex, occipitotemporal cortex, and occipitoparietal cortex (Figure 3a). Direct comparisons between the two tasks revealed higher cross-language pattern similarity for the semantic task than the naming task in the bilateral inferior frontal gyrus, middle temporal gyrus, inferior temporal gyrus, left fusiform gyrus, and angular gyrus (Figure 3b). Those results were still significant after controlling for behavioral performance (i.e., accuracy and reaction times; Figure S3). No brain regions showed the reverse effect.

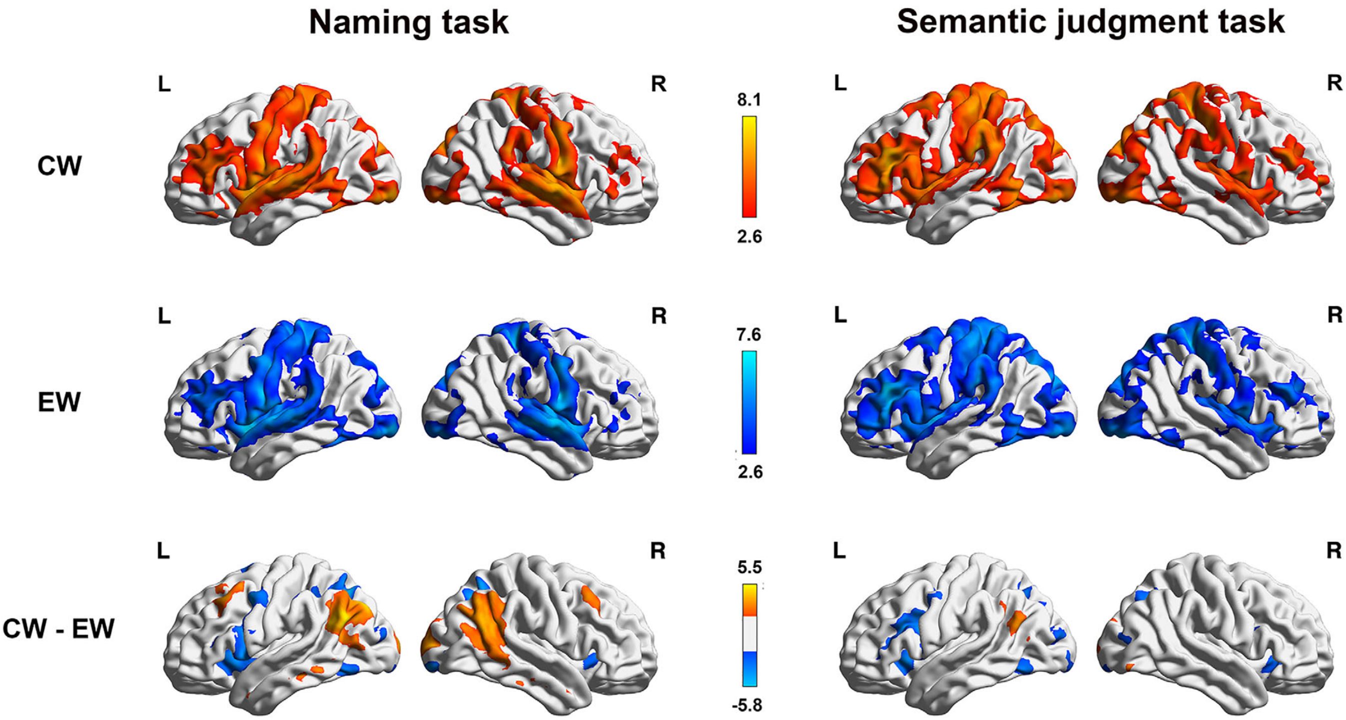

FIGURE 2 Group-level univariate activations for word reading during the word naming task (left panel) and semantic judgment task (right panel). Yellow in the top panel indicates the brain activations for Chinese words (CW). Blue in the middle panel indicates the brain activations for English words (EW). The bottom panel shows activation differences between Chinese and English words. Yellow indicates regions showing more activation for CW than EW. Blue indicates regions showing more activation for EW than CW. All activations were thresholded at $Z > 2.6$ (whole-brain corrected) and overlaid onto the group-averaged anatomical map. L, left; R, right

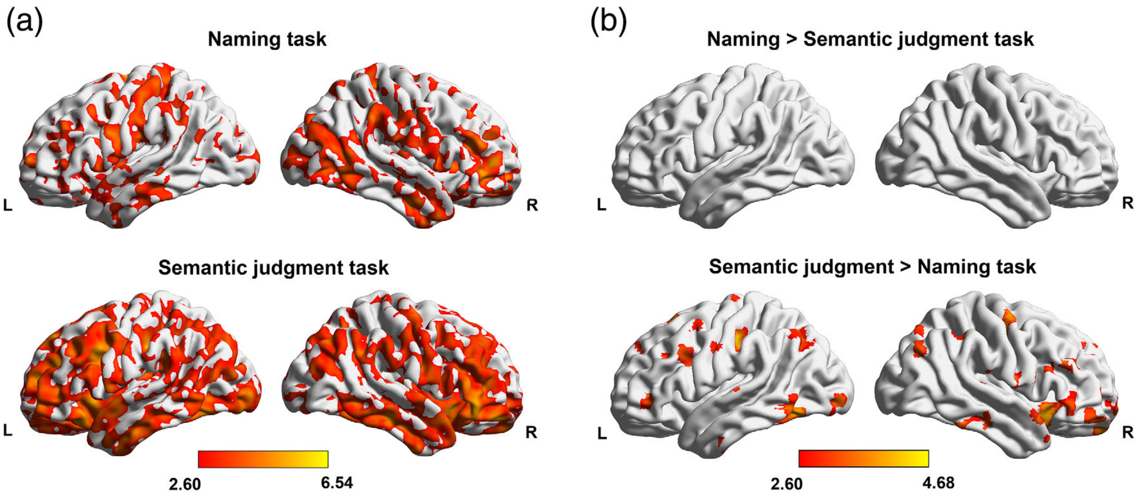

FIGURE 3 Brain maps for whole-brain searchlight-based representational similarity analysis. The left panel presents brain regions showing significant cross-language pattern similarity for the word naming and semantic judgment tasks (a). The right panel presents brain regions showing significant task differences in cross-language pattern similarity (b). The height threshold was $Z > 2.6$. L, left; R, right

The above results were mostly confirmed by ROI-based RSA. As shown in Figure 4, eight regions showed higher cross-language pattern similarity for the semantic task than for the naming task: left pars opercularis ($p = .010$), left orbitofrontal cortex ($p = .002$) left superior temporal gyrus ($p = .011$), left middle temporal gyrus ($p = .002$), left inferior temporal gyrus ($p = .009$), left fusiform gyrus ($p = .033$), left supramarginal gyrus ($p = .014$), and left angular gyrus ($p = .013$). No brain areas showed the reverse effect. These results indicate that, compared to shallow semantic processing (i.e., the word naming task), deep semantic processing (i.e., the semantic judgment task) enhanced neural pattern similarity between native and second languages in reading-related regions.

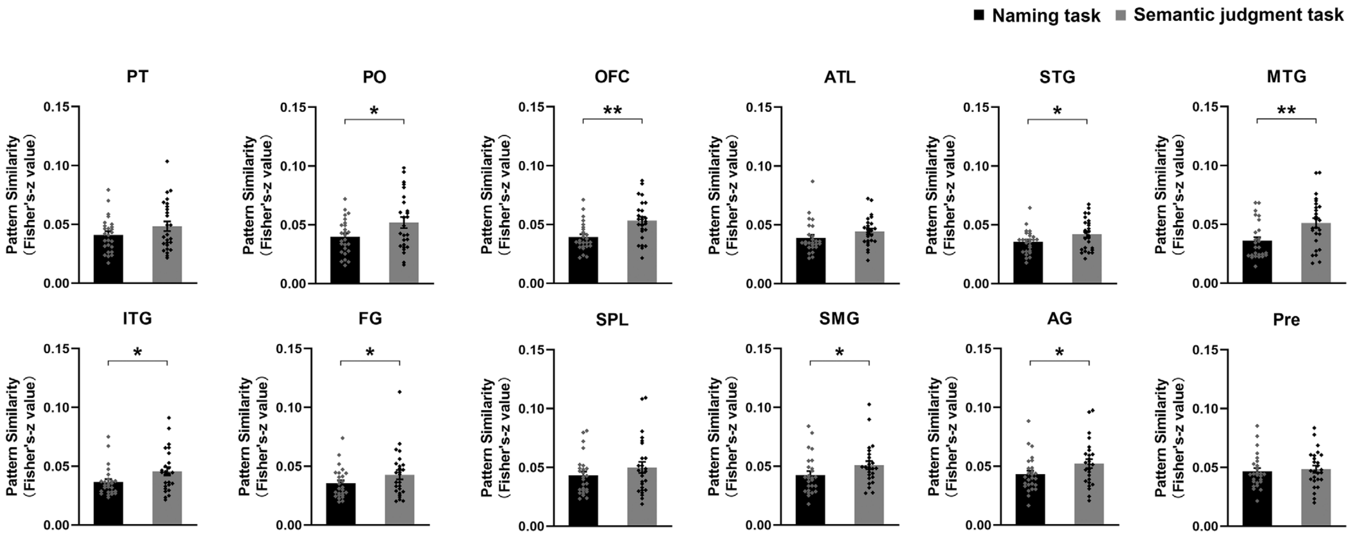

FIGURE 4 The effect of task on the cross-language pattern similarity in the 12 predefined ROIs for word reading. AG, angular gyrus; ATL, anterior temporal lobe; FG, fusiform gyrus; ITG, inferior temporal gyrus; MTG, middle temporal gyrus; OFC, orbitofrontal cortex; PO, pars opercularis; PRE, precuneus; PT, pars triangularis; SMG, supramarginal gyrus; SPL, superior parietal lobule; STG, superior temporal gyrus

6.4 | Associations between neural representations and lexical information within reading-related areas

This set of analyses was limited to the eight ROIs that showed greater cross-language pattern similarity in the semantic task than the naming task. Within-language nRDMs in those ROIs were correlated with within-language semantic prediction matrix. For the naming task, significant correlations were found in the left superior temporal gyrus ($r = 0.009$, $p = .003$), left inferior temporal gyrus ($r = 0.007$, $p = .025$), left supramarginal gyrus ($r = 0.011$, $p = .005$), and left angular gyrus ($r = 0.008$, $p = .030$). For the semantic task, significant correlations were found in the left pars opercularis ($r = 0.011$, $p = .003$), left superior temporal gyrus ($r = 0.008$, $p = .036$), left middle temporal gyrus ($r = 0.017$, $p < .001$), left fusiform gyrus ($r = 0.007$, $p = .030$), left supramarginal gyrus ($r = 0.015$, $p = .001$), and left angular gyrus ($r = 0.014$, $p = .001$). These correlations remained significant even after controlling for the visual and phonological prediction matrices (see Table S2). These results suggest that the brain regions mentioned above (i.e., those in the frontotemporal and temporoparietal cortex that showed greater cross-language pattern similarity for the semantic task than the naming task) indeed represented semantic information. Importantly, direct comparisons between the two tasks revealed that none of ROIs showed significant differences in within-language correlation (the smallest $p = .054$) or partial correlation (the smallest $p = .073$). These results suggest that task has a minimal effect on within-language semantic representations.

We then examined neural correlates of cross-language semantic representations by correlating the cross-language nRDMs with cross-language semantic prediction matrix. Significant correlations were found in five regions for the semantic task: left pars opercularis ($r = 0.011$, $p = .008$), left superior temporal gyrus ($r = 0.011$, $p = .007$), left middle temporal gyrus ($r = 0.012$, $p = .002$), left supramarginal gyrus ($r = 0.011$, $p = .001$), and left angular gyrus ($r = 0.009$, $p = .006$). No regions showed significant correlations for the naming task. Direct comparisons between the two tasks revealed that the correlations were higher for the semantic task than the naming task in five ROIs (the left pars opercularis: $p = .003$; left superior temporal gyrus: $p = .041$; left middle temporal gyrus: $p = .010$; left supramarginal gyrus: $p = .002$; and left angular gyrus: $p = .002$) (Figure 5). These results suggest that deep semantic processing relative to shallow semantic processing enhances cross-language semantic representations in reading-related regions.

7 | DISCUSSION

Using fMRI and RSA, the present study investigated the modulatory effect of the depth of semantic processing on cross-language pattern similarity in reading-related areas. In accordance with findings from previous bilingual studies, we found that reading words in the native and second languages generally elicited common activations in the typical reading-related regions, such as the bilateral prefrontal cortex, occipitotemporal cortex, and occipitoparietal cortex (Cargnelutti et al., 2019; Dong et al., 2020; Feng et al., 2020; Li et al., 2019; Liuzzi et al., 2019), although certain regions showed activation differences between the two languages in both the naming (Dong et al., 2020; Liu et al., 2010; Wang et al., 2020) and semantic tasks (Comstock & Oliver, 2021; Li et al., 2019). More importantly, both whole-brain RSA and ROI-based RSA revealed that cross-language pattern similarity during the semantic task (i.e., deep semantic processing) was higher than that during the naming task (i.e., shallow semantic processing) in select brain areas related to word reading. Meanwhile, based on the within-language versus cross-language semantic representation analysis, these brain areas also showed higher cross-language semantic

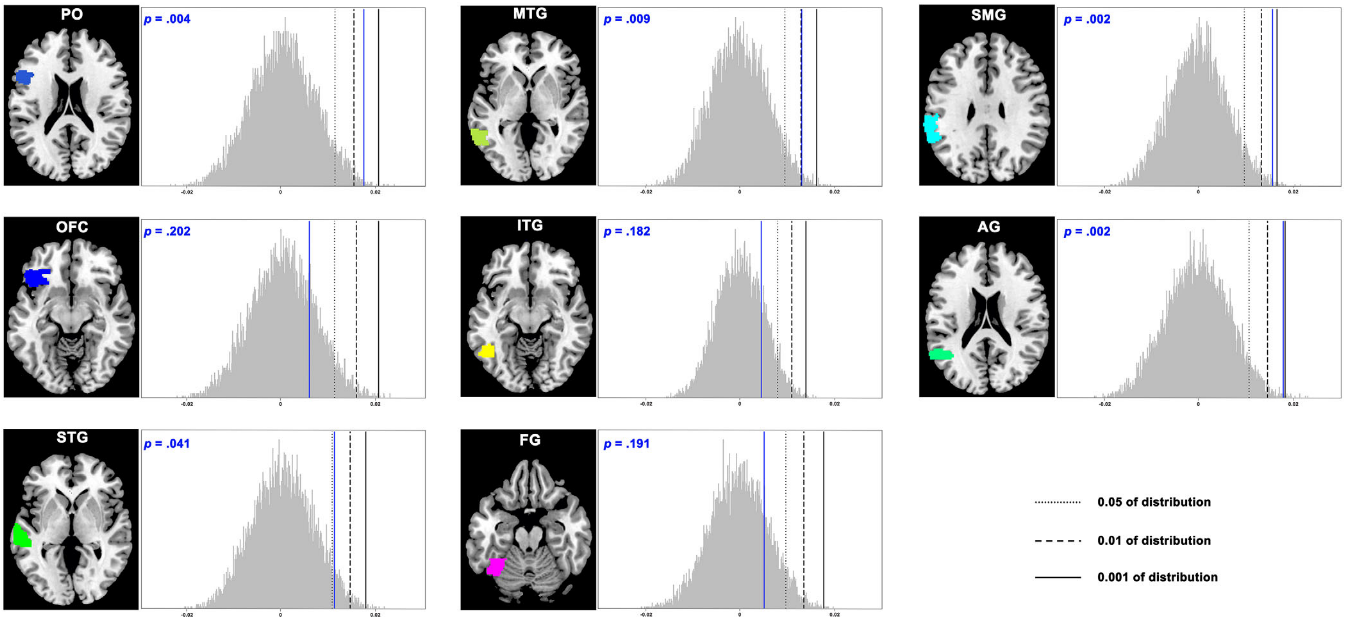

FIGURE 5 Histogram plots of paired-sample permutation tests for task differences in cross-language semantic representations. The blue line indicates the actual task differences in cross-language semantic representations. The three different black lines indicate the 0.05, 0.01, and 0.001 of the distribution, respectively. *X*-axis represents the task differences in cross-language semantic representations. AG, angular gyrus; FG, fusiform gyrus; ITG, inferior temporal gyrus; MTG, middle temporal gyrus; OFC, orbitofrontal cortex; PO, pars opercularis; SMG, supramarginal gyrus; STG, superior temporal gyrus.

representations in the deep semantic processing condition compared to the shallow semantic processing condition. Taken together these results, it seems that, deep semantic processing leads to cross-language semantic representations, which in turn leads to increasing neural pattern similarity between native and second languages.

Our results make several significant contributions. First, our results provided direct quantitative neuroimaging evidence for the influence of the depth of semantic processing on the neural pattern similarity between native and second languages. As mentioned in Introduction, by comparing neural activations of the semantic tasks with those of the non-semantic tasks (e.g., orthographic and phonological tasks) from different studies, we can infer that the depth of semantic processing may modulate the neural organization of native and second languages. Nevertheless, lacking direct comparison between different tasks and missed fine-grained multi-voxel pattern information in activation analysis prevented previous studies from drawing firm conclusion on the effect of the depth of semantic processing on cross-language pattern similarity. Here, by using a multivariate approach (i.e., representational similarity analysis), we quantitatively estimated neural pattern similarity between native and second languages and specified brain regions that showed the task effect on cross-language pattern similarity. Specifically, the depth of semantic processing influenced cross-language pattern similarity in select regions (i.e., the left inferior frontal gyrus, lateral temporal cortex, and temporoparietal cortex) in the reading network (Binder et al., 2009; Emmorey et al., 2013; Hodgson et al., 2021; Liuzzi et al., 2021; Price, 2012). These results provide experimental evidence for prior meta-analysis findings regarding task-related factors can influence cross-language similarity in neural activations (Comstock & Oliver, 2021).

It is worth noting that our results of task differences in the cross-language pattern similarity mainly reflected the effect of the depth of semantic processing but not of other irrelevant factors (e.g., task difficulty, phonological processing) for two reasons. First, significant task effects on the cross-language pattern similarity were still found in reading-related areas after controlling for the differences in behavioral performance (i.e., accuracy and reaction times) between the naming and semantic tasks as covariates in RSA. These results suggest that the impact of the differences in task difficulty was limited in this study. Second, both within-language and cross-language RSA revealed that regions showing differences in cross-language pattern similarity across the two tasks represented semantic information. The semantic representations remained significant after controlling for the visual and phonological prediction matrices. These results confirmed the modulatory effect of a semantic-related factor (i.e., the depth of semantic processing) on cross-language pattern similarity.

Second, our study disentangled the contributions of within-language and cross-language semantic representations to cross-language pattern similarity. Specifically, as the depth of semantic processing increases, greater cross-language semantic representations rather than within-language semantic representations were found in regions showing higher cross-language pattern similarity. These findings can be attributed to different mechanisms underlying within-language and cross-language information processing (Correia et al., 2014; Correia et al., 2015; Phillips et al., 2006; Xu et al., 2021). Previous research has revealed that within-language information processing relies on semantic relationships between words, as well as possible other relationships reflecting their individual properties (e.g., orthography, phonology), whereas cross-language information processing relies uniquely on language-independent semantic properties (Correia et al., 2014; Correia et al., 2015; Phillips et al., 2006). Given that cross-language semantic representations reflect common semantic representations between languages (Evans et al., 2019), and that deep conscious semantic processing is required for accessing to language-independent semantic representations (Sheikh et al., 2019; Xu et al., 2021), we can infer that, compared with the shallow semantic processing task, the deep semantic processing task might involve more cross-language (presumably language-independent) semantic processing, which leads to greater activation similarity between the native and second languages. This language-independent explanation seems to contradict with the results of nonsignificant differences in within-language semantic representation between the two tasks after controlling for visual and phonological information. It is possibly because the influence of language-specific nonsemantic information on within-language semantic processing was not completely eliminated through analysis of covariance.

Third, our results have important implications for understanding of the existing models of bilingualism, such as the Bilingual Interaction Activation (BIA+) Model (Dijkstra & van Heuven, 2002) and Multilink model (Dijkstra & Rekké, 2010). Although these models emphasize the role of task demands on bilingual word reading (Basnight-Brown, 2014; Dijkstra et al., 2019; Heredia et al., 2015), they did not specify how the depth of processing (a critical task-related factor) affects bilingual word processing. In addition, as these models are proposed for word reading in bilinguals whose native and second languages are alphabetic languages, they are still needed to be evaluated indifferent-script (e.g., Chinese–English) bilinguals (Abutalebi & Clahsen, 2019; Van Heuven & Wen, 2018). Therefore, our results of task effects on cross-language pattern similarity in Chinese–English bilinguals further our understanding of how task-related factor influence the bilingual word processing, and supported the universality of the existing computational models of bilingualism. Furthermore, our results also provide an explanation for prior findings of more robust cross-language priming effect in the semantic task relative to the phonological task (Kim & Davis, 2003; Meng et al., 2016). Specifically, compared to the phonological task, the semantic judgment task enhances cross-language semantic representations in regions related to reading, and consequently be able to prompt cross-language priming effect.

Three limitations of this study should be addressed in future studies. First, participants of our study were unbalanced Chinese–English bilinguals with intermediate proficiency in English. As discussed in the Introduction, it has been well-established that second-language proficiency plays a critical role in determining the degree of (dis)similarity in activation patterns between native and second languages (Bowden et al., 2013; Cao et al., 2013; Gao et al., 2017; Qu et al., 2019; Wartenburger et al., 2003), with higher second-language proficiency being associated with more similar activation patterns between native and second languages (Li et al., 2019; Sebastian et al., 2011; Stein et al., 2009; Xu et al., 2021). Furthermore, previous behavioral studies have indicated that access to the meaning of the second language can be influenced by second-language proficiency (Kroll et al., 2002; Kroll & Tokowicz, 2005; Van Hell & Tanner, 2012). Based on such evidence, we can infer that the contribution of the depth of semantic processing to cross-language neural representation may be modulated by proficiency in the second language. Therefore, future studies should examine the modulatory effect of the depth of semantic processing on cross-language pattern similarity by including bilinguals varying in second-language proficiency levels. Second, in this study, we computed a semantic category predicted matrix, in which items from different semantic categories were classed as dissimilar and those from the same category as similar. Although the binary semantic prediction matrix has been widely used to explore the semantic representation of native (Wang, Wu, et al., 2018; Xu et al., 2017) and nonnative languages (Dong et al., 2021; Evans et al., 2019; Taylor et al., 2019), our results may be further strengthened by future studies using a matrix with a graded measure of semantic similarity (e.g., rating-based semantic similarity) (Carota et al., 2021; Li et al., 2022; Wang, Xu, et al., 2018). Finally, due to the large noise in the scanner, the behavioral data of the word naming task was collected after scanning. Although the major conclusions in this study were drawn based on the MRI data, the lack of behavioral control of naming task is not optimal. Future studies should explore the effects of the depth of semantic processing on cross-language pattern similarity by recording subjects' oral responses during scanning.

In conclusion, our quantitative investigation revealed that, compared to the word naming task, the semantic judgment task enhanced cross-language pattern similarity in brain regions related to semantic processing, which results from increased cross-language semantic representations. These findings provide direct evidence for the modulatory effect of the depth of semantic processing on cross-language semantic representations, and contribute to a refined understanding of bilingual word representation.

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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